TP9251E

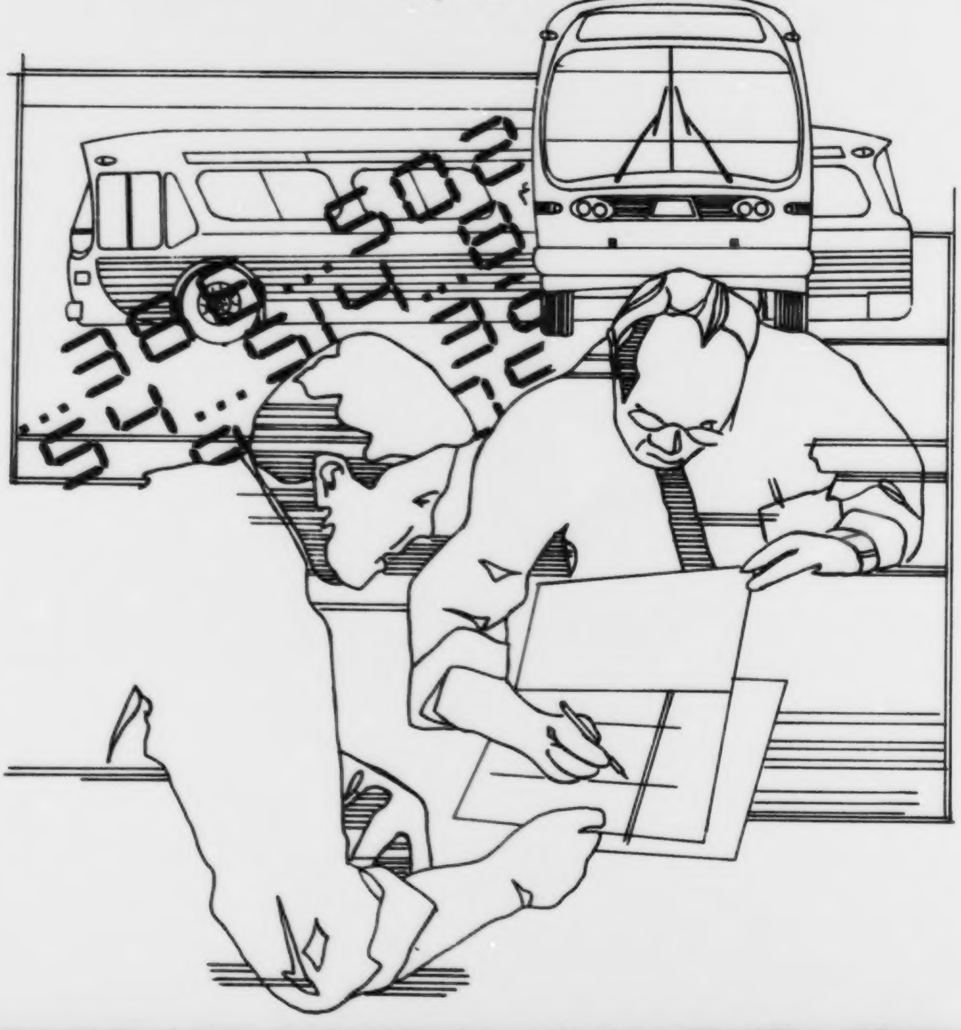
## FINAL REPORT

# AN EVALUATION OF VEHICLE DIAGNOSTIC SYSTEMS FOR BUSES

Prepared for the
Transportation Development Centre of Transport Canada,
the Ontario Ministry of Transportation and
the Canadian Urban Transit Association

by TransVision Consultants Ltd
in association with
Booz, Allen & Hamilton
Tandem Consultants Inc

May 1988



CA1
DTC 800
88
E88
c.2

89-04041/

Date Due

| | | | |
|---|---|---|---|
| SEP 5 1989 | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |

BRODART, INC. Cat. No. 23 233 Printed in U.S.A.

mm CA1
DTC800
88
E88
c.2

# AN EVALUATION OF VEHICLE DIAGNOSTIC SYSTEMS FOR BUSES

Library and Information Centre /
Centre de Documentation (GSLA)
RECEIVED - REÇU LE
JAN 24 1989
Transport Canada / Transports Canada

Prepared for
Transport Canada's Transportation Development Centre,
Ontario Ministry of Transportation and the
Canadian Urban Transit Association
by TransVision Consultants Limited in association with
Tandem Engineering and Management Consultants Inc. and
Booz, Allen & Hamilton Transportation Consulting Division
Authors: Tom Geehan, Gord Taylor and Mike Buckel
May 1988

407219

40354

"The contents of this report reflect the views of the contractor and not necessarily the official views of the Transportation Development Centre or the Ontario Ministry of Transportation."

Un sommaire en français de ce rapport est inclus avant la Table des matières.

**ACKNOWLEDGMENTS.** The authors of this report would like to express their sincere appreciation for the guidance and assistance provided by the members of the Steering Committe: **Jack Morgan,** Transportation Development Centre, Transport Canada; **Louis Strasberg,** Ontario Ministry of Transportation; and **Brendon Hemily,** Canadian Urban Transit Association.

A special gratitude is expressed to the transit maintenace managers and supervisors who shared their opinions with us on the direction of our efforts and who provided much needed data on transit maintenance requirements and costs. Finally, we thank the many suppliers and manufacturers for the information on systems and equipment provided for the study.

Transport Canada Transports Canada
Development Développement

# REPORT DOCUMENTATION FORM

1. Transport Canada Report No.
TP 9251E

2. TDC Project No.
6560

3. Recipient's Catalogue No.

4. Title and Subtitle
An Evaluation of Vehicle Diagnostic Systems for Buses

5. Report Date
May 1988

6. Performing Organization Report No.

7. Author(s)
Tom Geehan, Gord Taylor and Mike Buckel

8. Transport Canada File No.
T8200-6-6560/01-SD

9. Performing Organization Name and Address
TransVision Consultants Ltd.
3230 Chaucer Avenue
North Vancouver, B.C. V7K 2C3

10. DSS File No.
11SD.T8200-6-6560-A

11. DSS or Transport Canada Contract No.
T8200-6-6560/01-SD

12. Sponsoring Agency Name and Address
Transportation Development Centre (TDC)
200 Rene Levesque Blvd. West
Suite 601, West Tower
Montreal, Quebec H2Z 1X4

13. Type of Report and Period Covered

14. Sponsoring Agency Code
TDC 6560

15. Supplementary Notes
Co-sponsored by Ministry of Transportation, Ontario

16. TDC Project Officer
John H. Morgan

17. Abstract

Vehicles that break down in revenue service can be a major economic and public relations burden to transit managers. To reduce the occurrence of vehicle breakdowns, the use of increasingly sophisticated bus diagnostic systems is considered in this report.

The report outlines (1) the results of the investigation into current maintenance practices, (2) the state-of-the-art of vehicle diagnostic systems (3) the results of a detailed analysis of data on existing maintenance requirements and costs, (4) an investigation of the cost-effectiveness of diagnostic systems; (5) assessment of the issues involved in integrating diagnostic components with other communications, monitoring and maintenance management systems; (6) discussion of the key issues affecting vehicle diagnostic systems; and (7) definition of a program for further monitoring, coordinating and applying vehicle diagnostics in the transit industry.

Major concerns in the development of such a program include the interaction of the diagnostic systems with other forthcoming technological developments such as power management, multiplexing, electronic modules and other sensors and actuators. Major issues to be addressed include functional integration, feature consolidation, component modularity, systems standardization and component reliability. These issues and concerns lead to the conclusion that a strong reliance has to be placed on existing systems that are being developed in the trucking and automotive industries given the present well-developed state-of-the-art in transportation electronics.

18. Key Words
Transportation, Diagnostics, Monitoring, Electronics, Computers, Maintenance, Transit, Buses

19. Distribution Statement
Limited number of copies available from the Transportation Development Centre

20. Security Classification (of this report)
Unclassified

21. Security Classification (of this page)
Unclassified

22. No. of Pages
202

23. Price
Nil

TDC CDT 79-005
Rev 86

Canada

Transports Canada Transport Canada

Développement Development

# FORMULE DOCUMENTAIRE DU RAPPORT

1 Nº du rapport Transports Canada
TP 9251E

2 Nº de l'étude — CDT
6560

3 Nº de catalogue du destinataire

4 Titre et sous-titre
An Evaluation of Vehicle Diagnostic Systems for Buses

5 Date du rapport
mai 1988

6 Nº du rapport de l'organisme exécutant

7 Auteur(s)
Tom Geehan, Gord Taylor and Mike Buckel

8 Nº de dossier Transports Canada
T8200-6-6560;01-SD

9 Nom et adresse de l'organisme exécutant
TransVision Consultants Ltd.
3230 Chaucer Avenue
North Vancouver, B.C. V7K 2C3

10 Nº de dossier — ASC
11SD.T8200-6-6560-A

11. Nº de contrat — ASC ou Transports Canada
T8200-6-6560;01-SD

12. Nom et adresse de l'organisme parrain
Centre de développement des transports (CDT)
200 ouest, boul. René Lévesque
Suite 601, tour ouest
Montréal (Québec) H2Z 1X4

13. Genre de rapport et période visée
Final, mai 1988

14. Code de l'organisme parrain
CDT 6560

15. Remarques additionnelles
Co-sponsored by Ministry of Transportation, Ontario

16. Agent de projet — CDT
John H. Morgan

17. Résumé

Les pannes de véhicules de transports collectifs ont de sérieuses conséquences financières et posent de grands problèmes de relations publiques. Un palliatif suggéré est l'introduction de systèmes de diagnostic pour autobus, de plus en plus perfectionnés.

Le présent rapport : 1) donne un aperçu de la recherche sur les méthodes courantes d'entretien et 2) fait le point sur l'état d'avancement des systèmes de diagnostic pour véhicules routiers; 3) donne les résultats d'une analyse fouillée des données sur les besoins et les coûts relatifs à l'entretien, 4) dégage le rapport avantages-coût des systèmes de diagnostic, 5) approfondit les questions soulevées par l'intégration des systèmes de diagnostic avec les autres systèmes de communication, de surveillance et de gestion de l'entretien, 6) traite des aspects clés de toute la question des systèmes de diagnostic pour les véhicules routiers et, enfin, 7) définit un programme prospectif de surveillance, de coordination et d'utilisation de ces systèmes par les sociétés de transports collectifs.

Un facteur à prendre en compte dans la définition d'un tel programme est celui de l'influence que les systèmes de diagnostic envisagés peuvent avoir sur d'autres réalisations technologiques à venir, comme le contrôle moteur, le multiplexage de câblage, les modules électroniques ainsi que les capteurs et actionneurs. Parmi les questions à élucider doivent figurer l'intégration fonctionnelle, le regroupement des fonctions et la modularité, la standardisation et la fiabilité des composants. La conclusion à laquelle on aboutit est qu'il faut tabler avec confiance sur les systèmes existants qui s'intègrent petit à petit dans les secteurs du camionnage et de l'automobile grâce aux progrès fulgurants de la micro-électronique.

18. Mots-clés
Transports. Diagnostic. Surveillance.
Électronique. Ordinateurs. Maintenance.
Transports en commun. Autobus.

19. Diffusion
Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

20. Classification de sécurité (de ce rapport)
Non classifié

21. Classification de sécurité (de cette page)
Non classifiée

22. Nombre de pages
202

23 Prix
Aucun

CDT TDC 79-005
Rev 86

Canada

# SUMMARY

Vehicles that break down in revenue service can be a major economic and public relations burden to transit managers. To reduce the occurrence of vehicle breakdowns, many managers have implemented improved vehicle maintenance programs. Recent technological developments in microelectronics, radio communications, expert systems, and computers, however, may offer further opportunities to reduce vehicle breakdowns through the use of increasingly sophisticated bus diagnostic systems.

To take advantage of this new technology, a better knowledge is required concerning the status and potential of bus diagnostic systems, and further research is needed in order to: (1) identify the state-of-the-art of diagnostic systems, (2) investigate their application, and (3) explore the future possible directions of this technology.

In response to this need, the Ontario Ministry of Transportation and the Transportation Development Centre of Transport Canada, in cooperation with the Canadian Urban Transit Association, retained TransVision Consultants Limited to provide investigative and applicative research services in order to accomplish the following objectives:

1. To determine the state of the art of diagnostic systems for buses.
2. To identify those systems which may be applicable to the industry.
3. To develop a listing of bus functions and systems to be monitored.
4. To develop criteria for selecting promising applications for further consideration and research.
5. To identify critical issues and to assess the feasibility of introducing the most promising systems into transit.

The proposed research was, firstly, to result in conceptual, strategic and tactical plans for introducing appropriate sophisticated diagnostic systems which would take advantage of available technology in order to improve the efficiency and effectiveness of public transit. Secondly, by reviewing the state-of-the-art of diagnostic systems and the experience with this equipment, the research should improve the transit operator's ability to analyze his needs and facilitate the acquisition of equipment. Thirdly, by providing a forum for exchanging the experience of transit properties with more sophisticated diagnostic equipment, the research should bring to light improvements that might be made to existing designs as well as areas where new types of equipment might be needed.

To meet the requirements, to support the objectives and to achieve the anticipated benefits of this proposed study, the consultants undertook literature reviews, solicited appropriate information from equipment manufacturers, and conducted selected interviews with transit operators.

This final report on the results of the research project is viewed not only as an overview of the research effort but as a basis for facilitating discussion with respect to the application of diagnostic systems and expert systems in the transit industry.

The report outlines the results of the investigation into current maintenance practices and the state-of-the-art of vehicle diagnostic systems. It is noted in the report that the state-of-the-art is well advanced, but that the operators are unsure of the benefits to be achieved of any new system that would require vehicle retrofits. Newer, integral systems that are being built into engine and transmission components and are planned for braking systems appear to be more acceptable to the transit industry -- that is, the market appears to be driven by suppliers and as a fallout of new trucking technologies.

In the trucking industry, a standardized communication system has been developed by a joint committee of the ATA/SAE to join together different electronically-operated vehicle systems. This standard protocol for electronic components has received considerable support from the manufacturing industry and is a driving force behind new systems developments. It is proposed that the transit industry monitor these developments closely and, possibly, develop their own (albeit very similar) communication protocols. Another aspect of concern is the need for considerable software developments to analyze the information available from these systems on-board the vehicle and the expert systems aspects that this will entail.

The fallout from the trucking industry from integrated electronic components will probably affect the transit industry more than the development of any transit-specific on-board health monitoring systems. But the transit industry has to start preparing themselves for these changes.

The report also outlines; (1) the results of a detailed analysis of data on existing maintenance requirements and costs, (2) an investigation of the cost-effectiveness of diagnostic systems; (3) assessment of the issues involved in integrating diagnostic components with other communications, monitoring and maintenance management systems; (4) discussion of the key issues affecting vehicle diagnostic systems; and (5) definition of a program for further monitoring, coordinating and applying vehicle diagnostics in the transit industry.

An evaluation of diagnostic functions, maintenance problems and vehicle subsystems affected indicates that the cost-effectiveness of diagnostic systems on-board transit buses is such that transit agencies should be giving more consideration to this aspect than has been the case in their future maintenance and equipment acquisition programs. As with the case with many such new technological developments, however, senior governments will probably have to lead the way with selected development and demonstration programs to advance the technology and demonstrate the effectiveness of the diagnostic systems before individual transit properties will begin making proper use of these systems.

Major concerns in the development of such a program include the interaction of the diagnostic systems with other forthcoming technological developments such as power management, multiplexing, electronic modules and other sensors and actuators. Major issues to be addressed include functional integration, feature consolidation, component modularity, systems standardization and component reliability. These issues and concerns lead to the conclusion that a strong reliance has to be placed on existing systems that are being developed in the trucking and automotive industries given the present well-developed state-of-the-art in transportation electronics.

Therefore, a program is outlined in the report for the development and demonstration of a personal computer-based bus diagnostic system that would: (1) use existing technology (DDEC and ATEC), (2) utilize the ATA/SAE data communications protocol standard, (3) be expandable to include other subsystem diagnostics when available, and (4) incorporate expert type assistance in fault isolation.

It is stressed in the report that new technologies and strategies in transportation electronics will be heavily dependent on software development and it is recommended that senior governments cooperate to support these technologies so that systems and software will be developed that will meet the needs of the urban transit industry in Canada.

# SOMMAIRE

Les pannes de véhicules de transports collectifs ont de sérieuses conséquences financières en même temps qu'elles posent de gros problèmes de relations publiques. Un palliatif largement utilisé a été l'introduction de programmes d'entretien mûrement étudiés. Or, l'avènement de technologies récentes comme la micro-électronique, les télécommunications, les systèmes experts et l'informatique permet maintenant de déboucher sur des systèmes de plus en plus sophistiqués pour le diagnostic des véhicules de transport, systèmes grâce auxquels le nombre des pannes intempestives peut être davantage réduit.

Mais, pour tirer parti de toutes ces technologies, il faut approfondir les possibilités qu'offrent les systèmes de diagnostic par une recherche qui : 1) détermine l'état d'avancement de ces systèmes, 2) en explore les applications éventuelles et 3) en révèle l'évolution possible.

Dans cette optique, le ministère ontarien des transports, le Centre de développement des transports de Transports Canada et l'Association canadienne du transport urbain ont, de concert, confié à la firme TransVision Consultants Limited la tâche d'entreprendre une recherche exploratoire et d'applications visant les objectifs suivants :

1. Déterminer l'état d'avancement des systèmes de diagnostic pour les autobus.
2. Rechercher les systèmes qui conviennent à cette application.
3. Étudier une liste des circuits et systèmes devant être surveillés.
4. Étudier des critères pour la sélection des applications méritant une recherche plus poussée.
5. Dégager les aspects critiques de la question et évaluer la possibilité que les sociétés de transports collectifs puissent utiliser les systèmes les plus prometteurs.

La finalité de la recherche était triple : 1) dégager des plans de conception et d'applications stratégique et tactique permettant la mise en place de systèmes appropriés qui, en tirant parti des technologies existantes, débouchent pour leurs utilisateurs sur une exploitation plus rentable; 2) grâce au tour d'horizon des systèmes existants et de l'expérience acquise par leur utilisation, accroître l'aptitude des utilisateurs à mieux définir leurs besoins et, de la sorte, à faciliter le processus de décision et d'acquisition et 3) faciliter l'échange d'informations, notamment avec les sociétés de transport qui disposent déjà de systèmes de diagnostic avancés et, ainsi, mettre en évidence soit les perfectionnements susceptibles d'améliorer les performances, soit les secteurs pouvant se prêter à la mise en oeuvre de systèmes plus avancés.

Afin de respecter les exigences formulées, de donner suite aux objectifs fixés et de réaliser les avantages escomptés de la recherche, TransVision Consultants Limited a fait des recherches documentaires, a sollicité l'information voulue auprès des équipementiers et a mené des interviews auprès de sociétés de transports collectifs choisies.

Le présent rapport final peut être considéré non seulement comme un survol du domaine considéré, mais également comme la base d'échanges fructueux d'idées sur l'utilisation de systèmes de diagnostic et de systèmes experts par les sociétés de transports collectifs.

Le rapport présente les résultats de la recherche sur les méthodes courantes d'entretien et sur l'état d'avancement des systèmes de diagnostic pour véhicules routiers. Il fait remarquer que ces systèmes sont généralement assez avancés mais qu'il subsiste chez les utilisateurs éventuels des incertitudes quant aux avantages qu'ils pourraient en tirer, surtout dans le cas d'un système nécessitant des modifications aux véhicules mêmes. En revanche, ils sont plus favorablement disposés envers les systèmes qui font partie intégrante du moteur ou de la transmission et envers ceux dont on prévoit l'intégration aux circuits de freinage. Il apparaît donc que le marché subit la double influence des équipementiers et des retombées technologiques venant du secteur camionnage.

Celui-ci a adopté le protocole normalisé par le comité conjoint de l'American Trucking Association et de la Society of Automotive Engineers, pour faire communiquer entre eux deux systèmes électroniques incompatibles. Largement adopté par les équipementiers, ce protocole dynamise maintenant le processus de développement de systèmes avancés. Il est proposé que les sociétés de transports collectifs suivent ces développements de près et, peut-être aussi, qu'elles développent leurs propres protocoles, quitte à ce qu'ils n'en diffèrent presque pas. La mise en place de logiciels de plus en plus évolués, capables d'analyser l'information fournie par les systèmes embarqués, et la nécessité d'étudier des systèmes experts pouvant prendre cette fonction en charge sont autant de préoccupations nouvelles.

Les retombées technologiques découlant de l'intégration des composants électroniques, privilégiée par le secteur du camionnage, auront probable-

ment plus d'influence sur les transports collectifs que l'existence de systèmes de diagnostic mis au point exprès pour ces derniers. Quoi qu'il en soit, des changements se dessinent auxquels ils devront faire face.

En outre, ce rapport : 1) donne les résultats d'une analyse fouillée des données sur les besoins et les coûts relatifs à l'entretien, 2) dégage le rapport avantages-coûts des systèmes de diagnostic, 3) approfondit les questions soulevées par l'intégration des systèmes de diagnostic avec les autres systèmes de communication, de surveillance et de gestion de l'entretien, 4) traite des aspects clés de toute la question des systèmes de diagnostic pour véhicules routiers et 5) définit un programme prospectif de surveillance, de coordination et d'utilisation des systèmes de diagnostic par les sociétés de transports collectifs.

L'évaluation des fonctions se prêtant à un diagnostic, des problèmes relatifs à l'entretien et des sous-systèmes concernés montre que la rentabilité des systèmes de diagnostic embarqués pour les autobus urbains peut être telle que les sociétés concernées gagneraient à en envisager l'acquisition plus qu'elles ne l'ont fait jusqu'ici. Par ailleurs, à l'instar de ce qui se fait à l'égard d'autres progrès technologiques, il incombera aux gouvernements fédéral et provinciaux d'ouvrir la voie par le lancement de programmes sélectionnés d'exploitation expérimentale visant la mise au point des technologies concernées et de nature à convaincre les sociétés de transports collectifs de l'efficacité des systèmes de diagnostic.

Un facteur à prendre en compte dans la définition d'un tel programme est celui de l'influence que les systèmes de diagnostic peuvent avoir sur d'autres réalisations technologiques à venir, comme le contrôle moteur, le multiplexage de câblage, les modules électroniques ainsi que les capteurs et actionneurs. Parmi les questions à élucider doivent figurer l'intégration fonctionnelle, le regroupement des fonctions et la modularité, la standardisation et la fiabilité des composants. La conclusion à laquelle on aboutit est qu'il faut tabler avec confiance sur les systèmes existants qui s'intègrent petit à petit dans les secteurs du camionnage et de l'automobile grâce aux progrès fulgurants de la micro-électronique.

C'est pourquoi le rapport propose un programme pour la mise au point et l'exploitation expérimentale d'un système de diagnostic pour les autobus qui puisse fonctionner sur un ordinateur personnel et qui : 1) ferait appel à des technologies existantes (DDEC et ATEC), 2) utiliserait le protocole de communication normalisé ATA/SAE, 3) serait évolutif pour intégrer au fur et à mesure d'autres fonctions de diagnostic et 4) ferait appel à une aide de type "expert" pour la détection des défauts.

Le rapport, enfin, insiste sur le fait que l'utilisation de l'électronique dans le domaine des transports est lourdement tributaire des logiciels d'application disponibles et, dans cette optique, il recommande aux gouvernements fédéral et provinciaux de se concerter en vue de stimuler les technologies correspondantes de manière à réaliser des systèmes et des logiciels aptes à répondre aux besoins des réseaux de transport urbain au Canada.

# CONTENTS

**Introduction** .......... 1
Diagnostic Systems .......... 2
Expert Systems .......... 4
Research Program .......... 6
Research Report .......... 7

## Section 1: MAINTENANCE

**1. Maintenance Factors** .......... **11**
The Vehicle Fleet .......... 12
Maintenance Facility .......... 14
The Work Force .......... 15
Maintenance Practices .......... 18

**2. Maintenance Practices** .......... **19**
Maintenance Scheduling .......... 20
Information Systems .......... 21
Work Force Development .......... 22
Work Assignment .......... 22
Inventory Management .......... 23
Equipment Management .......... 24

**3. Maintenance Aspects** .......... **25**
Preventive/Corrective Maintenance .......... 26
Preventive Maintenance Scheduling .......... 27
Failure Pattern Analysis .......... 29
Maintenance Repair Policies .......... 30

**4. Maintenance Measures** .......... **33**
Labour Hour Requirements .......... 35
Maintenance Measures .......... 38
Total Maintenance Cost .......... 39
Maintenance Cost Breakdown .......... 40

## Section 2: DIAGNOSTICS

**5. Diagnostic Functions** .......... **47**
Maintenance Problems .......... 48
Diagnostic Functions .......... 49

**6. Diagnostic Parameters** .......... **53**
Diagnostic Parameters .......... 54

**7. Diagnostic Systems** .......... **61**
Existing Diagnostic Systems .......... 62
On-Line/On-Board Monitoring .......... 63
Off-Line/On-Board Monitoring .......... 68
Off-Board/Off-Line Monitoring .......... 70

**8. Diagnostic Summary** .......... **79**
Conceptual Diagnostic System .......... 80
Diagnostic System Priorities .......... 81

## Section 3: EVALUATION

**9. Evaluation Analysis** .......... **85**
Diagnostic Cost Savings Model (DIACSM) .......... 86
Maintenance and Diagnostics Analysis Model (MADAM) .......... 87
Maintenance Cost Savings with DIACSM Model .......... 88
Maintenance Cost Savings with DIACSM Model .......... 89
Qualification of the Analysis .......... 90

**10. Evaluation Results** .......... **91**
Evaluation Criteria .......... 92
The Options Considered .......... 92
Cost-Benefit Considerations .......... 95
Potential Benefits .......... 96
Some Preliminary Conclusions .......... 96

## Section 4: DEVELOPMENT

**11. Development Trends** .......... **101**
On-Board Vehicle Systems .......... 103
Systems Rationalization/Integration .......... 107

**12. Development Technologies** .......... **109**
Power Management .......... 110
Electronic Modules .......... 111
Sensors and Actuators .......... 112
Multiplex Communications .......... 113

**13. Development Strategies** .......... **115**
Functional Integration .......... 116
Feature Consolidation .......... 118

**13. Development Strategies (cont'd)** ........ **121**
- Component Modularity ........ 121
- Systems Standardization ........ 122

**14. Development Program** ........ **125**
- Proposed Development Concept ........ 126
- Technical Development Approach ........ 130
- Application of Proposed Concept ........ 131
- Conclusions and Recommendations ........ 134

**References** ........ **135**

**Appendices** ........ **139**
- A. Summary Maintenance Data ........ 139
- B. Diagnostic Cost Savings Model (DIACSM) ........ 153
- C. Maintenance and Diagnostics Analysis Model (MADAM) ........ 161
- D. Some Diagnostic Equipment Suppliers ........ 175
- E. SAE J1708 Recommended Practice ........ 179

# EXHIBITS

1. Example of an Off-Board Diagnostic System ................................ 2
2. Basic Structure of an Expert System.......................................... 5
3. Overall Approach to the Research Project ................................ 7

## Section 1: MAINTENANCE

4. Price Escalation of Buses............................................................ 12
5. Maintenance Practices and Activity Levels................................. 20
6. Basis of Statistical Preventive Maintenance................................ 26
7. Minimization of Maintenance Cost............................................... 27
8. Lifecycle Subsystem Cost Versus Time Interval............................ 28
9. Subsystem Performance or Condition Versus Life ......................... 29
10. Selection of a Maintenance Policy: Decision Tree........................ 31
11. Comparison of Maintenance Labour Hour Requirements................ 35
12. Some Maintenance Measures by Vehicle Subsystem ....................... 39
13. Comparison of Victoria and Mississauga Costs............................. 41
14. Maintenance Hours and Costs by Vehicle Subsystem ...................... 42
15. Comparative Maintenance Cost & Frequency by Subsystem .......... 43

## Section 2: DIAGNOSTICS

16. Comparative Costs - Engine Compression Failure.......................... 47
17. Diagnostic Problem-Function Interactions........................................ 50
18. Parameters for Vehicle Diagnostics ............................................. 54
19. Digital Tachometer...................................................................... 55
20. Digital Pressure/Vacuum Gauge .................................................. 55

21. On-Board Sensors for Transit Vehicles .......... 56
22. Cycle Event Sensor .......... 58
23. On-Board Vehicle Monitoring System .......... 65
24. Measuring Chart of a Tachograph .......... 68
25. An Electronic Data Recorder .......... 69
26. Detroit Diesel DDEC Diagnostic System .......... 71
27. Cummins CompuChek Diagnostic System .......... 72
28. Diagnostic Capabilities of Cummins CompuChek .......... 73
29. ABDS Hookup at Servicing Island .......... 75
30. ABDS Tests During Daily Servicing .......... 75
31. ABDS Maintenance/Inspection Application .......... 76
32. ABDS Tests During Complete Diagnostics .......... 76
33. Conceptual Comprehensive Diagnostic System .......... 80

**Section 3: EVALUATION**

34. Annual Savings in Maintenance Costs (DIACSM Model) .......... 88
35. Annual Savings in Maintenance Costs (MADAM Model) .......... 89
36. Benefit Cost Analysis of Alternative Concepts .......... 94

**Section 4: DEVELOPMENT**

37. Systems Integration/Rationalization .......... 102
38. Probable Future Diagnostic-Related Developments .......... 109
39. Typical Smart Actuator .......... 112
40. Multiplex System and Dual Power Supply .......... 113
41. Example of Functional Integration .......... 116
42. Multiplex Wiring System .......... 117
43. Low-Current Wiring System .......... 117
44. On-Board Network Integration .......... 118
45. Off-Board Network Integration .......... 119
46. Real-Time Control Network .......... 119
47. Generic Control Module .......... 122
48. Vehicle Installation of DDEC II .......... 126
49. Schematic Diagram of DDEC II .......... 127
50. Vehicle Data Communications .......... 128
51. DDEC II Diagnostic Data Reader .......... 129
52. Hierarchy of Diagnostic Tools .......... 129
53. Daily Test Information .......... 131

**APPENDICES**

A-1 Maintenance Data for Service/Cleaning .......... 140
A-2 Maintenance Data for Bus Inspections .......... 141

A-3 Maintenance Data for Body Repairs .......... 142
A-4 Maintenance Data for Engine and Fuel .......... 143
A-5 Maintenance Data for Braking System .......... 144
A-6 Maintenance Data for Electrical System .......... 145
A-7 Maintenance Data for Transmission .......... 146
A-8 Maintenance Data for Suspension/Steering .......... 147
A-9 Maintenance Data for Wheels and Tires .......... 148
A-10 Maintenance Data for Cooling System .......... 149
A-11 Maintenance Data for Heating/Ventilation .......... 150
A-12 Maintenance Data for Air System .......... 151
B-1 Diagnostic Cost Savings Model (DIACSM) .......... 154
B-2 Current Estimated Annual Maintenance Costs .......... 155
B-3 Distribution of Maintenance Labour by Purpose .......... 156
B-4 Magnitude of Diagnostic Function by Purpose .......... 157
B-5 Estimated Annual Savings with Diagnostic Systems .......... 157
B-6 Annual Savings in Maintenance Costs by Subsystem .......... 158
C-1 Maintenance and Diagnostic Analysis Model (MADAM) .......... 163
C-2 Mean Time Between Defects - MADAM Inputs .......... 164
C-3 Mean Person Hours Per Action - MADAM Inputs .......... 166
C-4 Mean Parts Cost Per Action - MADAM Inputs .......... 167
C-5 Reliability, Labour and Parts with/without Problems .......... 168
C-6 Mtce Costs with/without Problems (Maximum Savings) .......... 169
C-7 Assumed Diagnostic Improvement Functions .......... 170
C-8 Costs with/without Diagnostics (Probable Savings) .......... 170
C-9 Estimated Annual Savings with Diagnostics .......... 171
C-10 Annual Costs as Problem Magnitudes are Increased .......... 172
C-11 Annual Costs and Savings as Problems are Eliminated .......... 173

# INTRODUCTION

Vehicles that break down in revenue service can be a major economic and public relations burden to transit managers. To reduce the occurrence of vehicle breakdowns, many managers have implemented preventive maintenance programs and have set up tighter standards and controls for daily servicing and checking of vehicles. However, technological developments in microelectronics, radio communications, and computers may offer opportunities to reduce vehicle breakdowns even more through the use of increasingly sophisticated bus diagnostic systems.

Demonstrations are currently underway in several transit properties to develop systems that will enable microprocessors collecting information on-board vehicles to be in communication with a centralized operations centre and thus permit a better monitoring of vehicle location and status. Although these systems have been developed primarily to improve service, security and real-time information to users, they have also opened a path for reducing major vehicle breakdowns. In a few of these demonstrations, for example, the on-board microprocessor has been linked with certain engine and component warning signals. This allows specific functions to be monitored from the operations centre, permitting an earlier identification of potential problems, and facilitating a preventive response before the vehicle actually breaks down. In essence, these systems create a simple bus diagnostic system. More importantly, linking the various components in this way lays the groundwork for more elaborate systems that will improve vehicle maintenance even further by monitoring an increasing variety of vehicle components, and eventually by tracking the actual health of the specific vehicle. This will be feasible since the information collected can be stored and used in the system's on-going preventive maintenance activities.

To take advantage of this new technology will require a better knowledge concerning the status and potential of bus diagnostic systems, and research is thus needed in order to: (1) identify the state-of-the-art of diagnostic systems, (2) investigate their application, and (3) explore the future possible directions of this technology.

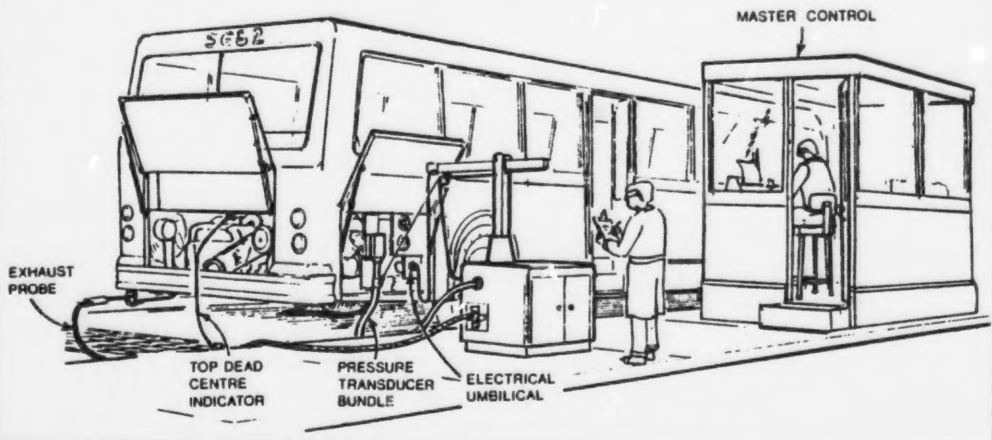
## DIAGNOSTIC SYSTEMS

The required technology is available for on-board vehicular diagnostic systems on surface transit systems. These systems have immediate economic benefits in terms of reduced incidence of downtime, reduced maintenance cost, and improved fuel economy.

Operators of public transportation systems have recognized these benefits and are now making use of automatic vehicle monitoring systems and off-board diagnostic systems to improve their service. The vehicle monitoring systems consist of vehicle location and status monitoring plus digital and voice communications systems and central monitoring and control systems. Off-board diagnostic systems include oil analyzers, electronic fuel injection diagnostic systems, and diesel engine diagnostic systems. Harris Corporation introduced a computerized electronic device for automated engine inspection and fault isolation in 1977. Cummins Engine Company introduced a diesel engine diagnostic tool called Compuchek in 1981 which is now being tested on London Regional Transport buses in England. And United Technologies developed and tested a prototype of an automatic bus diagnostic system in 1985 which combines a three-minute screening test at the fuel island with a 20-minute maintenance diagnostic test.

Exhibit 1

*Example of an Off-Board Diagnostic System*



But transit is not the only segment of the transportation industry which has expressed an interest in diagnostics:

**Rail Transportation** - The modern Japanese Shinkansen trains are making increasing use of on-board health monitors. General Electric has introduced a computer trouble-shooting system for diesel electric locomotives with built-in artificial intelligence and capable of calling up displays of drawings, photographs or films of the various locomotive components.

**Aviation Industry** - Increasing use is being made of microprocessors installed in both military and civilian aircraft to provide flight management, navigation, flight control and electric power control systems. These microprocessors not only provide flight crews with information to fly the aircraft more effectively, but carry out in-flight diagnosis of faults.

**Automobile Industry** - With demands for greater fuel economy and U.S. exhaust emission standards providing the impetus, microprocessors are now being built into automobiles in greater numbers, a trend that is forecast to accelerate, controlling engine performance and providing 'smart' suspensions. Because of their complexity, the manufacturers provide built-in diagnostic capability to assist garages in fault finding.

**Trucking Industry** - The new competitive environment for motor carriers is placing greater demands on management and increased sophistication is required. Standards for on-board microprocessors and their many sensors, activators and peripherals were developed by a joint committee of the American Trucking Association and the Society of Automotive Engineers.

**Marine Transportation** - To effect cost reductions and improve safety, automated systems have been in use for many years to navigate, control and monitor engine performance on-board ships. On-board computers are used to schedule preventive maintenance, document equipment system histories and inventory spare parts.

The proliferation of microcomputer-based engine control systems and the growing use of electronic dash panel displays in passenger cars and trucks has led transit operators to consider their use. Such instrumentation can offer a number of potential benefits to the transit operator, such as:

- rapidly alerting the driver to unsafe or equipment-damaging conditions,
- providing pre-trip checkout to minimize on-the-road downtime,
- recording transient malfunctions or out-of-tolerance conditions for post-trip analysis,
- improving the efficiency of maintenance personnel through computer-aided fault identification,
- supplying management information for improved trip scheduling and full vehicle utilization, thus replacing tachograph instrumentation.

A system capable of performing all the preceding functions would necessarily be complex. Moreover, the driver aid functions imply on-board data processing and display, while the maintenance-aid features imply on-board recording and off-board post-trip analysis.

## EXPERT SYSTEMS

It has been proposed that a knowledge-based or expert system would have the most potential for off-board post-trip analysis (1). An expert system is an attempt to improve the quality and efficiency of work performed by all maintenance personnel by making the knowledge of the best and most experienced maintenance staff immediately available.

Although expert systems use sophisticated computer and programming techniques, the power of such a system lies in the knowledge that it contains rather than in the hardware and software that make that knowledge available.

The history of expert systems dates back more than 20 years, but it is only in the last few years that they have been considered for general use. Systems are now being used in a wide range of applications, varying from the diagnosis of internal diseases to the diagnosis of faults in diesel electric locomotives to the configuration of computer systems. Other applications include air traffic control, simplification of symbolic mathematical expressions, and detection of geological deposits.

At one time it was assumed that the ability of a computer to calculate at high speed would allow problems to be solved by a process of evaluating all the possible alternative solutions. It soon became apparent that the combinatorial explosion of possibilities that arises with even a simple problem often makes this approach impractical. The answer was the introduction of heuristic rules, or rules of thumb, that human experts have developed to solve such problems.

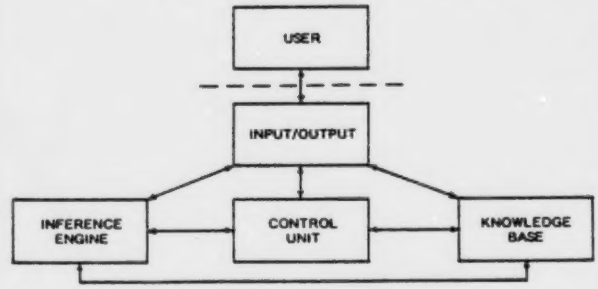
The use of heuristic rules is the basis of an expert system. The knowledge of an expert system consists of facts and heuristics. The 'facts' constitute a body of information that is generally agreed on by experts in the field. The 'heuristics' are mostly rules of good judgment that characterize expert-level decision-making in the field.

A knowledge-based system manipulates symbols rather than numerical values. Because of this, programs are generally written in a language like **LIS**t **P**rocessing (LISP) or **PRO**gramming in **LOG**ic (PROLOG). LISP is usually considered the 'assembler' of the expert systems while PROLOG lends itself to the heuristics. These are the two established languages in which most expert systems work has been carried out to date and both exist in numerous versions and dialects.

The four major elements of an expert system are: (1) a knowledge base which contains the 'facts', (2) an inference engine which contains the 'heuristics', (3) a control section which handles the operation, and (4) An input/output section for communicating with the user. Exhibit 2 on the following page shows the basic structure of an expert system.

*Exhibit 2*

***Basic Structure of an Expert System***



The knowledge base contains the basic data on the subject of the expert system. For example, if the expert system was concerned with diagnosis of faulty engines, the knowledge base would contain such data as the class of engine, nominal pressure measurements, injector settings, idling speed, fuel flow rate, etc.

The inference engine contains a set of rules that it has determined are used by the expert when dealing with his area of expertise. These are usually in a form: IF [conditions] THEN [actions]. For example, IF [the engine does not start] AND [the fuel gauge does not show empty] AND [the accelerator pedal has been depressed several time], THEN the engine has been flooded.

The control section is responsible for controlling the strategy to be used by the system. Two basic strategies of problem-solving are used by expert systems -- data-driven (or forward chaining) and goal-driven (or backward chaining). In the first approach, a unique solution is obtained for a given set of data. In the second approach, it is determined if all the data are consistent with an assumed solution. In practice many complex systems rely on both approaches and the approach that provides the most direct and unambiguous path between data and solution is considered to be the most probable. There does not, however, have to be a complete and unambiguous path from the data to the solution. This ability to operate successfully in the presence of data that are incomplete or imprecise makes expert systems particularly suitable for applications such as maintenance diagnostics.

The input/output section is critical to the success of the expert system. The majority of users are not usually experienced in the use of computers and yet are relatively expert in their own field. Any information that must be supplied by the user should be requested in a form to which the user can relate, and the output should be provided in the specialized language of the user. The input/output section for communicating with the user is usually in plain English and various input mechanisms for data, such as touch screens, are important.

A recent publication for Transport Canada (2) focused on the possible applications of expert systems in the Canadian transportation sector, as well as a detailed look at the characteristics of expert systems.

Considerable emphasis was placed on the problems of integrating expert systems with conventional data-processing applications, and of interfacing them with sensory and control systems. Two of the applications that were found to offer the most potential were: an on-board health monitoring system and a maintenance procedure expert system.

This was also the message from the participants of the R&D Needs Identification Workshop which CUTA held in 1985 (3): vehicle diagnostics was recognized as one of CUTA's 15 highest priority R&D needs.

## RESEARCH PROGRAM

To take advantage of these new technologies will require a better knowledge concerning the status and potential of bus diagnostic systems, and research is thus needed in order to: (1) identify the state-of-the-art of diagnostic systems, (2) investigate their application, and (3) explore the future possible directions of this technology.

Therefore, in response to this need, the Ontario Ministry of Transportation and Communications (Phase I) and the Transportation Development Centre of Transport Canada (Phase II) in cooperation with the Canadian Urban Transit Association, retained TransVision Consultants Limited in association with Tandem Engineering and Management Consultants Limited and the Transportation Consulting Division of Booz, Allen & Hamilton Incorporated, to provide investigative and applicative research services in order to accomplish the following objectives:

1. To determine the state of the art of diagnostic systems for buses.
2. To identify those systems which may be applicable to the industry.
3. To develop a listing of bus functions and systems to be monitored.
4. To develop criteria for selecting promising applications for further consideration and research.
5. To identify critical issues and to assess the feasibility of introducing the most promising systems into transit.

The proposed research would result in conceptual, strategic and tactical plans for introducing appropriate sophisticated diagnostic systems which would take advantage of available technology in order to improve the efficiency and effectiveness of public transit.

By reviewing the state-of-the-art of diagnostic systems and the experience with this equipment, the research should improve the transit operator's ability to analyze his needs and facilitate the acquisition of equipment.

By providing a forum for exchanging the experience of transit properties with more sophisticated diagnostic equipment, the research will bring to light improvements that might be made to existing designs as well as areas where new types of equipment might be needed.

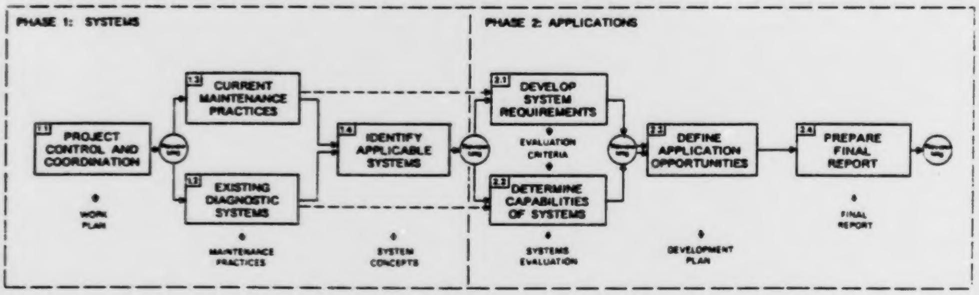
To meet the requirements, to support the objectives and to achieve the anticipated benefits of this proposed study, the consultants undertook literature reviews, solicited appropriate information from equipment manufacturers, and conducted selected interviews with transit operators.

### The Methodology

The overall methodology for the proposed research program included eight basic study tasks, segregated into two principal phases, as shown in the Exhibit below. Each task consisted of several additional subtasks and had a well-defined input and output.

*Exhibit 3*

***Overall Approach to the Research Project***


PHASE 1: SYSTEMS
PHASE 2: APPLICATIONS
1.1 PROJECT CONTROL AND COORDINATION
1.3 CURRENT MAINTENANCE PRACTICES
1.2 EXISTING DIAGNOSTIC SYSTEMS
1.4 IDENTIFY APPLICABLE SYSTEMS
2.1 DEVELOP SYSTEM REQUIREMENTS
2.2 DETERMINE CAPABILITIES OF SYSTEMS
2.3 DEFINE APPLICATION OPPORTUNITIES
2.4 PREPARE FINAL REPORT
WORK PLAN
MAINTENANCE PRACTICES
SYSTEM CONCEPTS
EVALUATION CRITERIA
SYSTEMS EVALUATION
DEVELOPMENT PLAN
FINAL REPORT

## RESEARCH REPORT

This report is viewed not only as an overview of the research effort but as a basis for facilitating discussion with respect to the application of diagnostic systems and expert systems in the transit industry. The structure of the report is outlined briefly below:

1. **Maintenance** reviews the major factors, various practices, aspects and relationships, and performance measures and costs of the maintenance function in the urban transit industry.
2. **Diagnostics** outlines the bus functions that can currently be monitored using various sensors and provides a review of the state-of-the-art of both on-board and off-board vehicle diagnostic systems.
3. **Evaluation** develops a listing of the various system requirements and selection criteria and identifies and assesses the feasibility of introducing the most promising systems into transit.
4. **Development** provides a discussion of the critical issues and assesses the feasibility of a possible development program for introducing the most promising applications into the transit industry.

# Section 1:

# MAINTENANCE

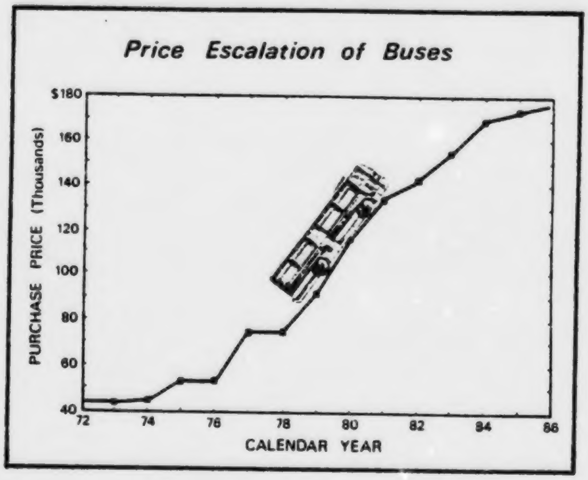
# 1. MAINTENANCE FACTORS

Maintenance is defined as the expenditure of effort and resources on a periodic but nonetheless continuing basis for the purpose of ensuring the optimum efficiency of a transit vehicle over its useful life.

The role of maintenance in a transit property is to provide the vehicles required for the performance of the planned operations at the time when these vehicles are needed and to assure that the vehicles are, and will continue to be, in safe operating condition. Maintenance, therefore, has no purpose in itself; it exists only as a support function. The service that a transit system can offer, however, is more than partially determined by the characteristics and capabilities of the maintenance system.

Every transit property is faced with maintenance of vehicles since it is the objective of every property to keep as many vehicles as possible in service. Each vehicle that is in the garage is a loss of revenue. For a transit system to operate in an efficient manner, the vehicles must receive proper maintenance and repairs with a minimum loss of time. It is the task of maintenance: (1) to service and maintain vehicles so as to minimize the number suffering breakdowns during operation, and (2) to perform the necessary servicing and maintenance in a way that limits the number not available for service.

With the ever increasing capital cost of buses (Exhibit 4) and the real decrease in financial resources for the transit industry, the properties are faced with this continuous problem of maximizing the use and availability of their equipment. The cost of downtime and spare inventory increases proportionally to the capital cost and thus there has been in excess of a 400 percent increase in these cost over the last 15 years.



Price Escalation of Buses

Exhibit 4

One of the ways that transit properties can offset this dramatic rise in the cost of buses is to improve the quality and efficiency of their maintenance function. In an attempt to determine the quality and efficiency of the maintenance function, transit properties in a number of cities were interviewed during the course of this study: Edmonton, Halifax/Dartmouth, Hull, Mississauga, Kitchener/Waterloo, Montreal, North Bay, Ottawa, Quebec City, Toronto, Winnipeg, Vancouver and Victoria. The basic objective of the survey was to collect data which described the existing maintenance practices and the incidence and costs of repair/failure by type of event.

The manner in which maintenance requirements are met varies from property to property, but the key factors affecting the quality and efficiency of a transit vehicle maintenance program are the fleet, maintenance facility, work force, and maintenance practices.

## THE VEHICLE FLEET

The characteristics of a transit system's fleet have an effect on the ability of the property to carry out an effective maintenance program. A basic consideration is the number of buses an operator has over and above the number needed to meet peak service needs (commonly referred to as the spare ratio). The age of the fleet also affects maintenance needs with older vehicles generally requiring more maintenance. Fleet mix (the number of types and manufacturers of buses that a system has), the quality of the equipment, and the degree to which an operator files manufacturer warranty claims on defective equipment and parts also have an impact on the maintenance costs of the fleet.

### Spare Ratio

Spare ratios reported by survey respondents ranged from 10 to 15 percent. In a similar survey in New York State (4), spare ratios ranged from 0 to 60 percent. The large operators had more consistent spare ratios than the smaller operators. The mean spare ratio for respondent operators with more than 100 buses ranged form 0.0 percent to 26.0 percent, with an average ratio of 13.4 percent.

An adequate spare ratio is essential for the establishment of a sound preventive maintenance program. Buses must be available to be worked on when mechanics are available. Although some preventive maintenance can be completed during off-peak hours, more time is required for maintenance work than is available between morning and evening peak service demands. It was found during the survey of Canadian properties that 7-10 percent are kept for spares for regular maintenance and another 3-5 percent may be kept as a field breakdown replacement pool. Spare ratios do not appear to be affected by differences in management structure, climate, population density, or size of fleet.

Operators with a low spare ratio requirement would naturally have difficulty in adhering to a routine preventive maintenance schedule, ultimately resulting in a shortened vehicle life.

### Age of Fleet

It seems, on the surface, fairly obvious that one of the major determining factors of an efficient maintenance program is the age of the vehicle fleet. Older vehicles would presumably be suffering more wear and tear and be more susceptible to breakdowns and other defects.

It is hypothesized that a correlation exists between maintenance costs and either one of two variables -- either the age of the last bus replaced or the average fleet age. Unfortunately, data to see if there is such an obvious correlation is lacking. A study in Chicago (5), however, showed a definite correlation between total miles on a vehicle and the maintenance and repair costs per mile. The maintenance costs increased substantially as the bus grew older with dips after the 100,000, 250,000, and 500,000 major overhaul points. The same study showed that the number of road calls per 10,000 miles (16,000 kms) for a bus with 500,000 miles (800,000 kms) on the odometer was almost four times the number of road calls for a bus with less than 100,000 miles (160,000 kms) on the odometer.

Operators with a high average vehicle age would probably have difficulty in maintaining an efficient routine preventive maintenance schedule, although the quality of maintenance affecting the vehicle life may well not be jeopardized in any way.

### Fleet Mix

A considerable body of literature on transit bus maintenance, and many maintenance personnel, agree that a mixed fleet hinders effective maintenance by placing added pressure on labour, inventory, inspection schedules, and record keeping. For each additional bus model, mechanics must be given specialized training, new parts ordered and stocked, operating schedules disrupted for different mileage inspection intervals, and separate books kept to monitor performance for each type of bus.

In order to avoid having a mixed fleet, most maintenance managers would probably prefer to purchase buses from one manufacturer on a continuing basis when a bus model is found that meets their needs. A fleet comprised of vehicles purchased from one manufacturer would reduce inventory needs, facilitate parts procurement, lessen the amount of mechanic training required, standardize inspection intervals, and enable the transit operator to establish an mutually-beneficial ongoing relationship with the manufacturer.

Unfortunately, for various reasons, a common vehicle fleet is usually not possible and may well not be desirable from an operational point of view. Another major deterrent to the continuing purchase of buses from one specified company has been the low bid requirement for capital purchases. Implementation of negotiated bidding in the United States is viewed a positive step towards more uniform vehicle fleets.

## MAINTENANCE FACILITY

The adequacy of the maintenance facility is a primary factor determining whether the property will have the ability to carry out an effective preventive maintenance program. A poor facility can result in a greater number of bus breakdowns and concomitant safety problems for transit riders, lowered employee morale leading to a poorer work product, and ultimately, a shorter lifespan for the vehicles housed and serviced.

A properly designed facility does not ensure that the maintenance program will be an excellent one, but an inadequate facility makes the achievement of an effective preventive maintenance program more costly and difficult. The most common problems with transit maintenance facilities are buildings not originally constructed for bus maintenance, deficiencies in garage design, and a facility too small to accommodate any increase in the number of buses.

Common problems are an insufficient number of service lanes and inadequate storage space for buses or parts. In addition, many older facilities are not designed for straight drive-through or for a minimum of right turns. A design allowing buses to be driven straight through the maintenance facility, with a minimum of backing up and right turns (which create a blind spot for the driver), is recognized as an efficient design and is incorporated into new facilities.

Although data is lacking to determine if differences in maintenance facilities result in differences in overall maintenance costs between transit properties, it is nonetheless believed that this is a contributing factor. A related factor is the method of bus storage. Several reports are good references for the design of maintenance facilities (6,7).

### Bus Storage

Most operators in Canada use indoor storage. Outdoor storage in cold weather contributes to difficulty in starting buses and freezing of bus subsystems. Relative to the first problem, engines of buses stored outdoors during cold weather are difficult to start in the morning unless engines are run all night, started every two or three hours, or attached to heater units.

Outdoor storage in cold weather may also result in the freezing up of buses' air suspension system and brakes, thereby increasing maintenance needs and creating potential safety hazards for passengers. Vandalism, in the form of physical damage to the bus, is also exacerbated by outdoor storage.

Buses that are washed and stored outdoors in freezing temperatures create a different type of undesirable situation: the water dripping off the buses freezes into ice puddles. The tires of the buses can become frozen into the ice. In addition, maneuvering buses on ice increases the potential for accidents. In summary, the problems involved with outdoor storage has led most operators in Canada to the use of indoor storage.

## THE WORK FORCE

The effectiveness of employees involved with the maintenance program -- mechanics, bus cleaners, and shifters -- is a major factor determining the ability of the transit system to adequately maintain its vehicles. Many variables influence the ability of these individuals to do their jobs, including the availability of training programs, attitude of management toward the maintenance function, adequate job descriptions, availability of job aids (including maintenance manuals), design of the workplace, and the driver's role in the maintenance program.

### Training

Transit properties in Canada generally have a consistent high level of mechanic training and it is difficult to determine the effect of poor training on maintenance costs. It is a factor, however, and the survey in New York State (4) revealed a significant difference in the mean percentage of operating costs devoted to maintenance for operators with a new mechanic training program and those operators without a training program -- 17 percent compared to 22 percent.

A consensus within the transit industry exists on the positive effect that mechanic training has on maintenance programs. Continuous training must be provided to upgrade maintenance skills and to orient mechanics to new equipment and state-of-the-art procedures.

Larger transit operators are better able to take advantage of training classes offered by bus and component manufacturers, in part because manufacturers may be unable to provide these sessions for systems with a small number of mechanics. Furthermore, smaller operators are not apt to have the time and extra personnel available to attend manufacturer-offered training sessions without shortchanging current maintenance operations. One solution to this problem has been the coordination of maintenance training programs on a regional basis by the Canadian Urban Transit Association.

### Management

The success of a maintenance program depends in large measure on the support of top management in terms of setting clear and concise objectives for the maintenance department. Goals for the maintenance program should be based on criteria that are capable of measuring the system's performance. There is a lack of consensus, however, on the most accurate measures of maintenance performance. Measures used include cost per service kilometer, percentage of trips completed, mean distance between failure and number of roadcalls.

Many suggestions have been advanced by management to improve the effectiveness of the work force. By assessing the exact nature of task requirements -- such as cleaning and servicing, inspection schedules, and major repairs -- maintenance managers can determine with a fair amount of precision the number and types of needed maintenance personnel.

Current techniques, however, are focused on controlling and monitoring daily activities (8). They do not produce the information needed to predict the impact of changes in the level and timing of maintenance or to evaluate alternative maintenance methods or schedules. Methods for vehicle replacement analysis are also not widely used. The absence of strategic planning can be attributed to the relatively recent concern about cost control in maintenance, the data requirements of strategic planning tools, and strong pressures on management to deal with day-to-day issues.

### Job Aids

Maintenance literature emphasizes the need for written job descriptions to enhance work expectations and employee accountability by helping employees to better understand their responsibilities and management to have more control over the maintenance process. Task descriptions and time standards are other methods used by management to increase human resource productivity. Strictly applied time standards, however, may be detrimental to effective maintenance because mechanics concerned about completing a job in a specified amount of time may be less thorough, or may not be able to take the time to make other adjustments or repairs found to be necessary.

Properly designed manufacturer's manuals can enhance the efficiency and effectiveness of bus repair. London Regional Transport, for example, has translated manufacturer's manuals into easy-to-read English to help mechanics understand manufacturers' maintenance recommendations.

Another factor often overlooked when evaluating the ability of maintenance personnel to do an effective job is the work environment. Minor modifications in building design, such as providing adequate work space and an employee lounge, can create a more positive work environment and, as a result, a better work product. One recommendation to improve maintenance effectiveness is to have common lounge facilities for drivers and mechanics to facilitate informal exchange between drivers and mechanics on general and specific bus problems.

### Driver Involvement

Driver involvement is a key element in the diagnosis of bus problems, and, hence, in promoting a successful maintenance program. Many transit properties direct drivers to turn in a bus defect card at the end of the work shift. These cards include spaces to indicate any bus malfunctions, and sometimes include a space to report bus body damage. Detailed and accurate report cards assist mechanics in determining the repair needs of a particular vehicle.

The Central New York Region Transportation Authority (CENTRO), in Syracuse, has implemented an innovative program to register driver's post-trip reports. Believing that written drivers' reports often did not contain adequate information for mechanics to do the required repairs on the vehicles, a bus reporting booth was constructed as the initial stop of the bus servicing lane at CENTRO's new Syracuse facility. An individual trained to trouble-shoot bus problems is assigned to sit in this booth and to question drivers verbally as they return with the buses to obtain specific and detailed information on any problem(s) the driver had with the bus. This procedure provides more accurate reports and facilitates a more efficient work-flow pattern because it allows each bus to go immediately to the proper area of the garage for servicing.

Training bus operators in proper bus operation is a obvious means for lengthening bus life and reducing maintenance costs because the vehicles last longer when drivers treat the buses with more care. One suggestion to increase the care drivers take with the bus is to pair each driver with the same vehicle every day. Thus, in the same way a driver gets to know the family car, the bus driver would become extremely familiar with the bus and could immediately identify potential problems on a day-to-day basis. In theory, the bus would become the driver's and would be apt to be treated with more care. Many operators reported they would prefer to utilize pairing, but do not have the extra parking space needed to allow a driver to have access to the same bus every day.

## MAINTENANCE PRACTICES

The final major factor that influences the quality and efficiency of a transit vehicle maintenance program is the particular maintenance practices that are utilized. These are discussed in greater detail in the following chapter. In general, however, maintenance of vehicles comprises three essential groups of operations:

- Preventive maintenance: these are periodical inspection or replacement operations for the purpose of preventing breakdowns and extending the vehicle's life;
- Overhauling operations: these are large-scale operations carried out at infrequent intervals at the end of the 'life cycle' of one of the vehicle's major component;
- Repair operations: these involve prompt action connected with the inevitable accidental damage arising for reasons usually impossible to forecast (traffic accidents, etc.).

Application of particular maintenance practices must be matched to the three essential groups of operations to achieve the most efficient maintenance program. The trade-off is between regular and non-regular maintenance and, usually, an intermediate form is found, consisting partly of regular maintenance and partly of maintenance in the case of failures.

Other practices also play a part. For instance, the replacement (rather than in-frame repair) of entire components is often advantageous since it reduces the time for which the vehicle is off the road, provides specialization of work, savings on the actual repair of components by repairing a number of components at a time, etc.

In the following chapter, the different and varied maintenance practices that are used in Canadian transit properties are reviewed.

# 2. MAINTENANCE PRACTICES

To set the stage for this discussion of maintenance practices, a generalized maintenance program can be outlined as follows: After each day's operations, buses are cleaned inside, filled with fuel and may also be cleaned on the outside. In addition to these housekeeping and refuelling operations, maintenance tasks are performed according to an inspection and lubrication schedule based on time and the distance covered. A general test of serviceability is performed daily, and this is backed up at longer intervals, depending on the distance travelled, by the thorough inspection on important components (9,10).

For practical purposes, a special form, designed as a check-list, for each maintenance period is used. When the work has been performed, the respective items on the check-list are crossed off and the form is then signed by the maintenance staff. Repair operations cannot be planned in accordance with a predetermined timetable applied to maintenance and servicing operations. Despite this, in order to make sure that the work is carried out in as rational a manner as possible, careful job-preparation, scheduling and parts-handling procedures are utilized (11).

The manner in which maintenance requirements are met and the practice used varies from property to property, but the key factors affecting the quality and efficiency of a transit vehicle maintenance program are the fleet, maintenance facility, work force, and maintenance practices.

Many other characteristics that are unique to each transit property also may have an effect on the type of maintenance program that is used. Site-specific factors influencing maintenance needs include type of routes the bus runs (express, local, charter), terrain over which the bus runs, the age of the bus, climate, number of hours the bus runs per day, and load factors. Each of these factors influences the types of needed repairs. For example, older buses typically require correction of corrosion damage or engine overhauls, and buses on routes requiring many stops need additional transmission and brake adjustments and repairs.

Exhibit 5 illustrates various maintenance practices and activity levels roughly according to the size of the operation.

Exhibit 5

***Maintenance Practices and Activity Levels***

| MAINTENANCE ACTIVITY | SMALL TRANSIT PROPERTY 10-Bus Fleet | MODERATELY SMALL TRANSIT PROPERTY 50-Bus Fleet | MODERATELY LARGE TRANSIT PROPERTY 200-Bus Fleet | LARGE TRANSIT PROPERTY 500-Bus Fleet |
|---|---|---|---|---|
| **Maintenance scheduling** | No scheduled inspections on most items. | Manufacturer's inspection guidelines. | Individually tailored inspection intervals. | Scheduled replacement intervals |
| **Information systems** | Aggregate; manual; direct entry; nonintegrated. | Automated; microcomputer. | Micro/mini; indirect entry. | Disaggregate information; automated; mainframe computer; integrated. |
| **Work force development** | No training, seniority promotion, no incentives, no work standards. | Outside training; nonmonetary incentives. | Merit promotion, monetary incentives, work standards. | In-house training. |
| **Work assignment** | Contract out heavy repairs, in-house inspection; first-come, first-served. | Some heavy repairs done in-house; maintain and repair quickest item first. | Spectroanalysis augments spection; priority for scheduled work over breakdown, | All repairs in-house |
| **Labour allocation** | All crews responsible for all duties; no specialized mechanics, crews, teams; one shift. | Specialized mechanics; two shifts. | Specialized crews; three shifts. | Specialized teams. |
| **Inventory management** | No formal structure except minimum safety levels. | Manual systems; defined order quantities, reorder points; safety stock defined through service levels. | Computerized system. | Computer system directly integrated with maintenance scheduling; order quantities and reorder points contingent on scheduling. |
| **Equipment management** | Low capital intensity | Moderate capital intensity with minimum special equipment | Moderate capital intensity with selected special equipment items. | High capital intensity with specialized equipment. |

Source: Adapted from Reference 12

## MAINTENANCE SCHEDULING

The preventive maintenance schedules of most transit properties are established on set mileage intervals. Some operators, however, may utilize schedules based on days (e.g., every other Tuesday, bus 346 is scheduled for a preventive maintenance check). Other properties base preventive maintenance on the number of hours a bus is in service. Interestingly, many operators using mileage intervals do not utilize odometers or hubometers as a part of the maintenance program, and rely instead on trip logs to estimate mileage.

The type of preventive maintenance schedule is not as important a factor in preventive maintenance as is strict adherence to the schedule chosen. If inspections are not performed as scheduled and mileage intervals between inspections exceed the established schedules, the probability increases that buses will malfunction or break down, creating an unsafe situation for passengers and resulting in a shorter vehicle lifespan.

Manufacturer's specifications for inspection intervals are usually used as a basis for the formation of the preventive maintenance schedule with adaptations made at each property to accommodate unique operating conditions and needs. A written maintenance plan (outlining maintenance goals, preventive maintenance schedules, and repair policy) helps to clearly identify the procedures and expected results and improves the maintenance effort.

## INFORMATION SYSTEMS

### Record Keeping

A recurrent situation found during the property survey part of this study is the need for improvements in record keeping. One measure of the quality of record keeping at a bus system is the ability to determine maintenance cost per bus. Most operators are unable to determine maintenance cost per bus. The survey revealed records are not always organized in such a manner as to enable the operator to readily determine maintenance cost per vehicle or are not being used effectively.

There is a correlation between maintenance cost per bus and the percentage of operating cost devoted to maintenance. As an industry average, the mean percentage of operating cost devoted to maintenance was about 19.1 percent from the latest edition of the CUTA fact book.

Many transit operators have begun to use record-keeping data to strengthen the planning process of their maintenance program. If a system can predict accurately when a bus component will fail, management may be able to avoid expensive emergency repair by replacing the component before breakdown. As record keeping is expanded to incorporate additional vehicle components, maintenance problems become more predictable and more activities can be added to preventive maintenance checklists. Replacement of components before failure is not always cost-effective. By utilizing vehicle and component records, the operators can compare the cost of the alternative maintenance methods, such as replace-at-failure and replace-before-failure, per component to determine the most efficient method.

### Use of Computers

The computer is an essential part of a records management program, yet only 6 of 49 systems in Canada have computerized maintenance programs (13). Twenty-six other systems were in the process of implementing a computerized maintenance system or expected to be computerized within three years, but 17 systems indicated computerization is not expected. The larger the system, the greater the propensity to use computerization as a maintenance aid. Many of the smaller operators did not believe computerization would benefit their operation because their fleets were small enough that their maintenance programs could be managed manually -- even though inexpensive programs are available for personal computers.

The computer system should provide basic information on buses, maintenance work performed, and preventive maintenance schedules. Before purchasing a computer, management should assess its objectives and search the market for the proper computer software.

## WORK FORCE DEVELOPMENT

Transit properties in Canada generally have a consistent high level of mechanic training and it is difficult to determine the effect of poor training on maintenance costs. It is a factor, however, and the survey in New York State (4) revealed a significant difference in the mean percentage of operating costs devoted to maintenance for operators with a new mechanic training program and those operators without a training program -- 17 percent compared to 22 percent.

A consensus within the transit industry exists on the positive effect that mechanic training has on maintenance programs. Continuous training must be provided to upgrade maintenance skills and to orient mechanics to new equipment and state-of-the-art procedures.

Larger transit operators are better able to take advantage of training classes offered by bus and component manufacturers, in part because manufacturers may be unable to provide these sessions for systems with a small number of mechanics. Furthermore, smaller operators are not apt to have the time and extra personnel available to attend manufacturer-offered training sessions without shortchanging current maintenance operations. One solution to this problem has been the coordination of maintenance training programs on a regional basis by the Canadian Urban Transit Association.

## WORK ASSIGNMENT

### Contracting Out Work

Some transit properties contract out maintenance work. The smaller operators are most apt to contract work out because of the lack of facilities or equipment, or both. Quite often engine work is contracted out because it would not be cost-effective for an operator to have on hand the equipment necessary for this type of repair. Contracting out maintenance work may be a desirable approach to solving certain problems, but may create additional problems if the contractor is incapable of providing adequate service. If contracting out is a normal practice with the transit property, it is essential that careful records be kept of the costs for each repair category.

## INVENTORY MANAGEMENT

Parts availability is important to the planning and efficiency of the maintenance operation. If parts are unavailable, the necessary repair work cannot be completed. An unacceptable, but common occurrence, is that of buses waiting to be repaired because a specific part is not available. This problem occurs for two reasons -- the part is too expensive for the property to keep it in stock, or planning for inventory levels is inadequate.

The result of a lack of adequate inventory planning is insufficient space for inventory, resulting in unorganized parts storage. Several visited operators had to stock parts outside the inventory room in a disorganized pile because of insufficient space, making efficient ordering, receiving, inspecting, locating, and dispensing of parts difficult.

A second problem, often related to poor inventory practices, is overstocking of parts resulting from inadequate receiving and inventory control procedures. Valuable inventory space may be lost if parts are ordered without proper monitoring. Many bus systems utilize card systems to keep track of the parts in stock and to determine when to reorder a specific item. Other operators, however, employ computer systems for these purposes. Fourteen of 49 systems in Canada use computers for materials management (7). The biggest problem with both methods, revealed by site visits, is the lack of constant updating of information on when parts had been used or reordered, producing incorrect records of inventory levels. It is important that management receive accurate and timely inventory reports to enable realistic projections of parts needs.

Computers are the most desirable method for keeping track of inventory because a large volume of information can be reviewed in a short period of time and part reordering can be facilitated in a timely fashion. Inventory practices also can be influence by the fleet mix. Having a variety of bus makes and models in the fleet requires the purchase of a greater variety of parts, complicating inventory and its record keeping.

Establishing and following inventory practices proven to be effective is important to ensure that needed parts are available. It was recommended by transit managers and related literature that a locked parts area with access limited to few people be utilized and that a physical inventory of all parts be conducted at least once a year. The best parts procurement systems kept price quotations on file for frequently purchased items obtainable from more than one vendor, thereby allowing the inventory manager to quickly order the needed parts at the lowest price.

## EQUIPMENT MANAGEMENT

### Diagnostic Techniques

As an aid to proper planning and increased efficiency of maintenance, many operators take an oil sample form each bus on a regular basis and analyze the sample. The analysis allows managers to determine the optimal time for oil changes and to identify certain engine problems. Significant benefits include an extension of time between oil change intervals, a lengthening of the life of engine coolants, and enhancement of the ability of maintenance personnel to project the life span of engine components.

All the maintenance facilities relied on standard garage tools and mechanic skills for the diagnosis of bus problems. In almost all the larger properties there were dynamometer facilities which are used for quality control on major repairs. In one property, this facility was used for routine inspection of power train performance. Many other maintenance superintendents did not believe this procedure to be cost effective.

The current systems do not perform any diagnostic functions, but can usually identify "problem" vehicles by use of exception limits in their maintenance information system. No property surveyed had any of its shop floor instrumentation tied directly to the vehicle database.

Diagnostic testing is another preventive maintenance technique. Computerized test equipment to monitor and diagnose bus component problems can often identify minor mechanical problems before major repairs are required. One system currently used is the Automated Bus Diagnostic System (ABDS), which can be used to perform 69 different tests and is designed to reduce unplanned maintenance and to verify that corrections have been made. Siemens, a West German company, has developed a similar diagnostic system that is capable of performing 120 to 170 tests and reducing the time required for inspections. Most bus operators in Canada do not have sophisticated diagnostic equipment because of its cost and the general belief that the equipment is not yet 'perfected'. Existing diagnostic systems will be discussed in greater detail in Chapter 7.

# 3. MAINTENANCE ASPECTS

Transit managers have long been aware of the importance of maintenance, and they have developed a number of tools for improving its effectiveness. These methods include pre-run inspections, roadcall reporting, work order processing, and preventive maintenance scheduling systems. These tools are generally quite useful for managing daily operations. However, effective maintenance requires attention to a number of other concerns. These include fine detail items such as how to best perform a specific maintenance task, as well as more global questions involved in setting preventive maintenance policies and schedules and projecting future budget needs. In this chapter, some of the more global aspects will be reviewed.

Research done on bus fleet management has found that the availability of maintenance information is the key to making efficient management decisions (8). Management decision-making information should include more than just the day-to-day records collected on daily work flows. It should also include information on expected work flows so that daily scheduling can be conducted, information on future work flows so that labour force requirements and parts inventory levels can be planned, and information on the distribution of component failures through time so that efficient repair policies can be planned. The only efficient means of obtaining the necessary information on a regular basis is through a computerized maintenance management system.

Some of the aspects and relationships that help to provide answers to these concerns include: percentage of preventive maintenance required, scheduling of preventive maintenance, failure pattern analysis, maintenance repair policies and, of course, detailed analysis of repair costs by component. These are considered in the following pages.

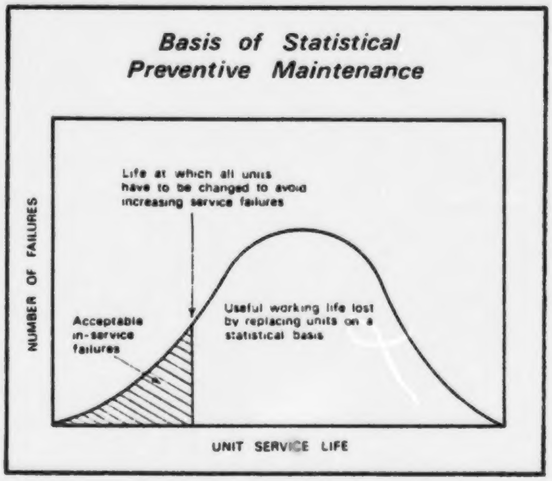
## PREVENTIVE VS CORRECTIVE MAINTENANCE

Transit vehicle fleets have two categories of maintenance: preventive maintenance (PM) is performed to forestall failure mechanisms, and corrective maintenance (CM) is performed to correct a failure that has already occurred. The former means taking any steps necessary to avoid failures occurring in service and includes both routine scheduled maintenance services and unit replacement at statistically determined periods within their anticipated life.

During preventive maintenance inspections, fluids and filters are changed and component checks and adjustments are made. A less common type of preventive maintenance is to preventively remove and replace parts or components in advance of their failure. For example, a transit agency might routinely overhaul all engines that haven't failed by a specified mileage even if they are still working properly. In such cases, it is determined that the engines are close to the end of their design life.

The problem with statisically based preventive maintenance is that inevitably a large proportion of it is done in advance of it actually being necessary, as shown in Exhibit 6 opposite. For example, units will be replaced while still working satisfactorily and having a useful working life remaining. The scatter of engine life achieved in service is actually so wide that removal and overhaul on a statistical preventive mainenance basis is prohibitively expensive.

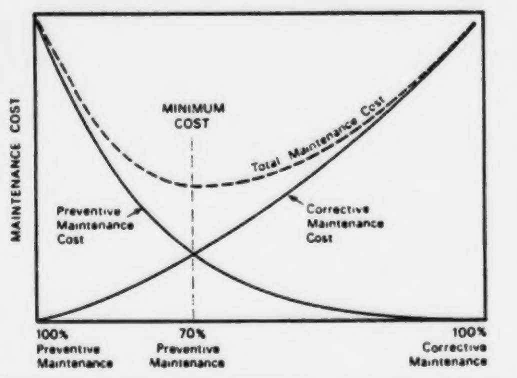
Exhibit 6


**Basis of Statistical Preventive Maintenance**

Corrective maintenance is carried out to repair a part or component after it has failed. There are trade-offs that must be made between the levels of corrective and preventive maintenance that are carried out. Suppose, for example, that only minimal preventive maintenance tasks are performed and only fluids and filters are changed at inspection intervals without making any other checks or adjustments. All other maintenance is executed on a corrective basis. In this situation, buses are run until something fails. The maintenance department is in a situation largely of responding to failures instead of anticipating them. This limits the ability to plan and schedule maintenance activities. If the bus fleet is relatively low on spares, it places the maintenance department in a continual cycle of making emergency repairs to meet peak period demands for buses. Buses are then tied up in maintenance instead of being on the street.

*Exhibit 7*

**Minimization of Maintenance Cost**



As preventive maintenance is increased, the amount of emergency repairs should decline, increasing the efficiency of the maintenance operation and resulting in better control of costs. Exhibit 7 depicts the relationship between total maintenance cost, the cost of corrective and preventive maintenance and the amount of preventive maintenance that is conducted. As the level of preventive maintenance effort increases, corrective and total maintenance costs decrease. The optimum level of preventive maintenance is where the total cost of preventive and corrective maintenace reaches a minimum. The problem for the maintenance manager is to find the efficient level of preventive maintenance for each component which results in the minimum total maintennace cost. Several studies have indicated that this is at a level where 60 to 70 percent of the maintenance is preventive maintenance and 30 to 40 percent is unscheduled corrective maintenance (14).

It is worth noting that the true cost of corrective maintenance is difficult to establish. The loss of revenue earning capability while the vehicle is off the road, the cost of vehicle recovery if a failure occurs on the road, the overhead cost of providing a replacement vehicle and the cost of lost passenger confidence in the service must all be added to the basic repair cost. It is therefore common to underestimate these costs, giving the impression that a higher proportion of unscheduled work is acceptable and therefore less preventive maintenance should be performed.

## PREVENTIVE MAINTENANCE SCHEDULING

Preventive maintenance and periodic inspection currently is scheduled by simple time or service functions -- the passage of calendar time or the accumulation of vehicle kilometers. Generally, however, the distribution of failures versus time or distance is quite broad and the only preventive maintenance policy possible has shorter intervals than the optimum frequency of maintenance. This policy will result in higher maintenance costs and lower fleet readiness.

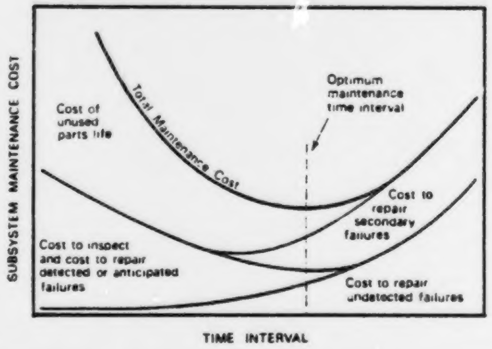
Several methods are available for determining maintenance intervals for components of transit buses. Four models are described in detail by Rueda and Miller (15). They include the Jardine model, the Dynamic

Programming model, the Bakr Maintenance Scheduling model, and the Masstram system. The Maintenance Analysis and Scheduling System for Transit Management, or Masstram model, for example, searches for the maintenance schedule which minimizes preventive maintenance and in-service failure costs, and also satisfies user-provided constraints on peak requirements and allowable in-service failures. These more advanced maintenance schedule optimization techniques have considerable potential but large data requirements and a number of assumptions that reduce the probability of their application in the near future.

Transit vehicles are comprised largely of subsystems (or components) which exhibit wear-out characteristics with normal failure distributions. It is important with such subsystems to minimize the occurrence of failures, and the unscheduled corrective maintenance that follows, without introducing excessive periodic inspection or preventive maintenance activities. Exhibit 8 illustrates the relationship between the total maintenance cost and the maintenance time interval.

*Exhibit 8*

***Lifecycle Subsystem Maintenance Cost Versus Time Interval***



The maintenance cost versus maintenance time interval function for a given vehicle subsystem exhibiting wear-out must contain a minimum at some service interval, since **more frequent** maintenance would:

- Use less of the inherent component life, causing greater parts consumption,
- Increase opportunities to induce failures as a result of flawed inspection/maintenance procedures, and
- Increase vehicle downtime.

and **less frequent** maintenance would:

- Increase frequency of in-service field failures (road calls),
- Increase secondary failures induced by the primary in-service failures,
- Increase both maintenance costs and downtime due to the secondary failures.

Although the aforementioned scheduling models will assist in developing better maintenance schedules, maintenance policy should be based on the failure distribution that is assumed to apply to the system elements. This really requires some form of health monitoring. Maintenance before failure is appropriate for systems exhibiting wear-out but not for stochastically failing systems with declining or constant failure rates.

## FAILURE PATTERN ANALYSIS

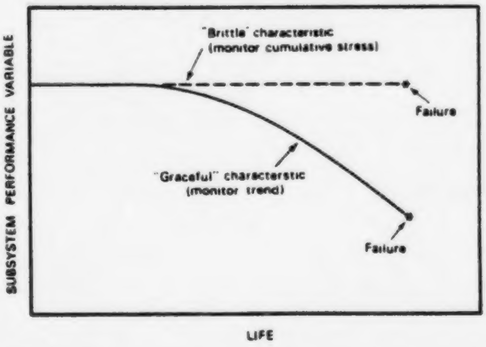
**Stochastic Failures.** In stochastic systems, failure time distributions can be measured at aggregate levels of assembly since cumulative stress histories for individual failure mechanisms are unknown and component quality variations are unknown. In some systems, notably electronic systems, it is not practical to track individual failure mechanisms. These systems are complex, with a profusion of components and failure mechanisms, and their operating time constants are short.

**Mechanical Failures.** Mechanical systems, on the other hand, are less complex and have long parameter change time constants. With mechanical systems, it is possible to monitor the key failure mechanisms at the subsystem and component level (especially with a computer).

Monitoring mechanical systems would make it possible to track important individual degradation mechanisms. If the parameter(s) that characterize degradation can be defined so that relatively narrow failure distributions result, these measurements can be used to schedule anticipatory maintenance just prior to failure, with significant cost and readiness benefits. Since currently there is little such monitoring, many transit vehicle subsystems (engines, brakes, transmission, etc.) are allowed to fail, with little attempt to obviate the failure through anticipatory maintenance, resulting in large disbenefits in costs and readiness.

*Exhibit 9*

***Subsystem Performance or Condition Versus Life***



Time function characteristics of vehicle subsystem degradation may be 'brittle' or 'graceful', as shown in Exhibit 9. A brittle characteristic may be typified by brake system lining wear-out, where a change in performance may go unnoticed until catastrophic failure or damage occurs (often resulting in secondary damage). A graceful characteristic may be typified by engine power output degradation, where noticeable poor performance usually occurs prior to a catastrophic event.

Improving the efficiency of maintenance operations starts with an understanding of the nature of each component failure. A fuse, for example, is as good as new until a short circuit occurs and the fuse fails. This understanding of failure patterns determines the appropriate type of maintenance for each component and enables the development of an effective maintenance policy.

## MAINTENANCE REPAIR POLICIES

There are four ways to deal with the maintenance of a part or component: condition-based maintenance, fixed-mileage maintenance, operate-until-failure maintenance, and design-out maintenance (16).

**Condition-Based Maintenance (CBM).** With condition-based maintenance, approaching failures are predicted when a monitorable condition reaches a level where it exceeds a tolerable limit. Reduced maintenance costs can be derived from new techniques to anticipate failure so that maintenance can be performed just before the probability of failure. This process is also called anticipatory maintenance (AM). The use of CBM (or AM) will concurrently reduce the requirement for corrective maintenance.

Condition-based maintenance is appealing for several reasons. CBM detects maintenance problems before the bus becomes inoperable, thus reducing the chances of an in-service failure. Also, CBM means early detection of a problem before it mushrooms into a catastrophic failure. The part or component is repaired shortly before it ultimately fails. It is used until nearly the end of its life, thereby getting maximum use out of the component while avoiding the consequences of failure. Finally, chance failures are eliminated allowing the manager to execute preventive repairs according to the maintenance department's schedule.

There are three commonly performed types of condition-based monitoring of components: qualitative inspections, quantitative inspections, and trend monitoring. Qualitative inspections are periodic checks of a component's condition, such as the visual inspection of the tires. Quantitative inspections are checks which measure the condition of a component to see if it exceeds a tolerable level, such as the inspection of brake shoe thickness to see if the brakes should be overhauled. Trend monitoring are quantitative measures of past experience to set a norm, such as the monitoring of fuel and oil consumption rates.

**Fixed-Distance Maintenance (FDM).** These are maintenance actions that are carried out at regular interavals. This type of maintenance is most applicable where there is a relationship between the distance travelled and the failure mechanism. For example, oil and oil filters are changed at specific intervals because they are known to deteriorate with use.

In general, condition-based is preferable to fixed-distance maintenance. This is because there is a degree of chance variation in the failure of all parts and components. Condition-based maintenance permits the maximum use to be obtained from each component without allowing the component to fail and makes it possible to schedule repairs in advance. Fixed-distance maintenance implies the establishment of blanket repair policies across all parts of a specific type. Some parts would be repaired too soon and some may fail before the proposed interval.

**Operate-Until-Failure Maintenance (OUF).** Operating a part or component until it fails implies that all maintenance will be corrective. Because failures are random events, a component or part that is not being monitored can fail without warning and maintenance work flows cannot be planned and scheduled. Generally, an operate-until-failure maintenance policy is the least perferable strategy for the maintenance of a part or component in terms of work flow management, as well as safety. It is, however, the most cost-effective policy if the condition of the part or component cannot be monitored and/or the failure mechanism is not distance-dependent. It also may be preferable if the total cost of repair after failure is equal to the cost of repair before a failure.

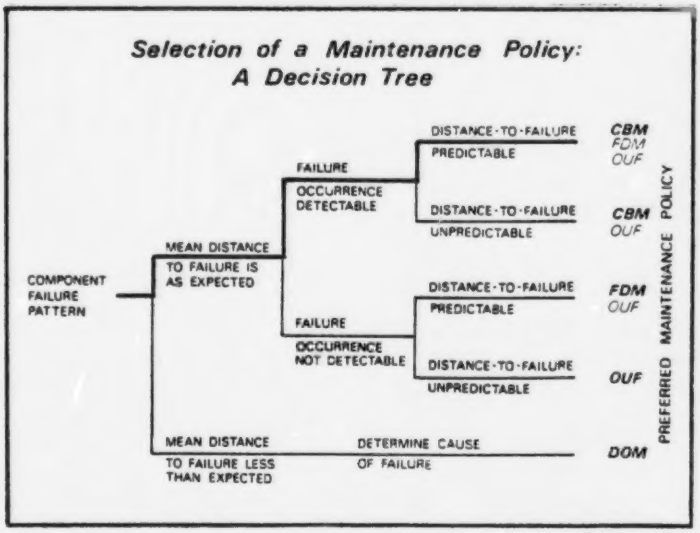
**Design-Out-Maintenance (DOM).** The designing out of maintenance problems as a policy is different in objective than the three previously discussed policies because DOM seeks to remove the maintenance problem. The other policies seek to minimize maintenance problems. It is really an idealistic approach since it is beyond most transit operators. The objective is reduce maintenance costs by having the manufacturer redesign the component or for the transit agency to purchase an alternative component or system.

### Selection of a Maintenance Policy

Each possible maintenance repair policy has advantages and disadvantages and is applicable to specific parts or components depending on a number of aspects. These various aspects are illustrated in the decision tree in Exhibit 10. As an example, consider brake shoes: brake shoe wear is detected by monitoring the thickness of the brake shoes, hence the failure occurrence is predictable; the distance to failure is also predictable. The decision tree path for this case is highlighted with a bold line. The possible maintenance policies, in order of preference, are condition-based maintenance (CBM), fixed-distance maintenance (FDM), and operate-until-failure (OUF). The preferred policy, CBM is first to indicate the preference. Economic and safety factors would only enhance this preference.

*Exhibit 10*

***Selection of a Maintenance Policy: A Decision Tree***


COMPONENT FAILURE PATTERN
MEAN DISTANCE TO FAILURE IS AS EXPECTED
FAILURE OCCURRENCE DETECTABLE
DISTANCE-TO-FAILURE PREDICTABLE
CBM
FDM
OUF
DISTANCE-TO-FAILURE UNPREDICTABLE
CBM
OUF
FAILURE OCCURRENCE NOT DETECTABLE
DISTANCE-TO-FAILURE PREDICTABLE
FDM
OUF
DISTANCE-TO-FAILURE UNPREDICTABLE
OUF
MEAN DISTANCE TO FAILURE LESS THAN EXPECTED
DETERMINE CAUSE OF FAILURE
DOM
PREFERRED MAINTENANCE POLICY

Source: Reference 11

# 4. MAINTENANCE MEASURES

Goals for the maintenance program should be based on criteria that are capable of measuring the system's performance. There is a lack of consensus within the transit industry on the most accurate measures of maintenance performance. Some operators use maintenance cost per service mile, some use cost per hour, some use mean distance between failure (MDBF), others use percentage of scheduled trips completed, and some miles per liter of fuel.

One measure of performance that provides an indication of the effectiveness with which bus maintenance is being performed is the number of road calls that occurs. The utilization of this MTBD value as a performance measure is considered to be undesirable by many transit managers. A common criticism of the measure is the inconsistent definition of 'road call'. Several systems define 'road call' as any radio call requesting assistance, including those for broken mirrors and windshield wipers; other operators narrowed the term to any mechanical breakdown and still others reported a road call only when a bus was unable to continue in route service. However, data prepared by APTA (1) show that the median mileage between road calls for mechanical failures is between about 4,000 and 6,000 kilometers (around once a month).

Road calls should be a particularly appropriate measure of the quality of maintenance because each road call represents an unscheduled activity and frequently an interruption of service. On the one hand, there is an unnecessary expense; on the other, a failure to provide a reliable service. Both have an adverse effect on the transit system. Although a dollar value can be expressed for the cost of a road call (even though it is difficult to find a transit system that can report what the cost is), it is more difficult to express the adverse impact on transit revenues of unreliable operation. Because of this, frequently a comparison is only made between the costs of road calls versus the additional maintenance costs that could be incurred in an attempt to reduce them. Obviously some balance must be maintained.

Due to the difficulty in obtaining accurate data on road calls or mean time between defects, more emphasis is placed in this study on costs, particularly man-hours of labour and costs by subsystem or component on the bus per year or per 50,000 kilometers of travel. This emphasis on costs, which includes costs of road-calls, allows for more comparisons between different data sources and provides for a more reliable estimate.

Cost information was obtained from several of the many transit properties that were contacted during the course of the study. In the following pages and, in more detail, in Appendix A, detailed maintenance cost information by vehicle subsystem is presented based on several sources of data. Some comparisons are also provided to confirm the reliability of the data. It was noted that the annual number of defects times the mean time to repair should equal the annual labour hours for a vehicle subsystem and this fact was used to confirm some of the data. The major sources of data are:

- Detailed computerized maintenance records for the month of October 1987 for the **Mississauga** Transit System.
- Summary data broken down by vehicle system and labour and parts for a nine-month period in 1987 for the **Victoria** Transit System (detailed component hours and costs were also available but could not be aggregated for comparison).
- Summary maintenance manpower requirements by vehicle subsystem as reported in NCTRP Report 10 from the Transportation Research Board for fifteen **American** transit agencies (17,18).
- Detailed reliability data for the Toronto Transit Commission as reported in the **Ontario** MTC Report RR217 for mean time between defects in kilometers (19).

The maintenance data from Mississauga was the most detailed, allowing calculation of labour hours, materials cost, mean time to repair (MTTR), mean time between defects (MTBD), and number of occurrences of defects. Each of these factors was calculated for each vehicle subsystem. The resulting data was then compared with other sources to determine its reasonableness.

In almost all cases, the Mississauga data was very comparable to other data. The major exception was in the calculation of the mean time between defects from the Ontario MTC study -- large differences occurred which may be due to the fact that the Ontario data was not reported in as fine a detail as the Mississauga data.

## LABOUR HOUR REQUIREMENTS

In an attempt to develop some disaggregated maintenance cost data, some interesting results were used from the National Cooperative Transportation Research Project (17). In this project, maintenance manpower requirements on the basis of detailed work activities were developed by vehicle sub-fleet and functional area for properties in the United States. A series of statistical applications were made to compare the range of maintenance requirements and account for variances in time to repair and frequency of repair by vehicle system and subfleet. The manpower utilized by public transit bus operators was reported by vehicle subsystem and by major work activity. These values were converted to metric units for comparison with the Mississauga data in the table below.

*Exhibit 11*

***Comparison of Maintenance Labour Hour Requirements***

| Vehicle | American Data | | Mississauga Data | | Difference | |
|---|---|---|---|---|---|---|
| Subsystem | Hours | Percent | Hours | Percent | Total | Percent |
| Service/Cleaning | 111.2 | 23.8% | 108.0 | 23.0% | -3.2 | 2.9% |
| Bus Inspections | 77.7 | 16.7% | 74.2 | 15.8% | -3.5 | 4.5% |
| Body Repairs | 71.0 | 15.2% | 66.0 | 14.1% | -5.0 | 7.0% |
| Engine and Fuel | 50.9 | 10.9% | 50.7 | 10.8% | -0.2 | 0.4% |
| Braking System | 40.0 | 8.6% | 41.4 | 8.8% | +1.4 | 3.5% |
| Electrical System | 30.2 | 6.5% | 33.8 | 7.2% | +3.6 | 11.9% |
| Transmission | 23.7 | 5.1% | 27.4 | 5.8% | +3.7 | 15.6% |
| Suspension/Steering | 17.5 | 3.7% | 20.3 | 4.3% | +2.8 | 16.0% |
| Wheels and Tires | 15.8 | 3.4% | 14.3 | 3.1% | -1.5 | 9.5% |
| Cooling System | 12.0 | 2.6% | 14.0 | 3.0% | +2.0 | 16.7% |
| Heat/Ventilation | 8.8 | 1.9% | 9.9 | 2.1% | +1.1 | 12.5% |
| Air System | 7.3 | 1.6% | 9.5 | 2.0% | +2.2 | 30.1% |
| TOTAL | 466.1 | 100.1% | 469.5 | 100.0% | +3.4 | 0.7% |

As illustrated in the table, the total annual manpower requirements for maintenance of a bus is about 470 hours (assuming that a bus travels about 52,000 kilometers per year). The results from the Mississauga data and the American data are also very comparable. The manpower utilized by vehicle subsystem and by major work activity is discussed in further detail in the following paragraphs.

**Servicing and Cleaning.** The amount of labour-hours spent on servicing and cleaning is a function of the amount of time required to perform each activity and the number of vehicles serviced and cleaned. There are usually three primary activities for servicing and cleaning staff: daily servicing, major interior cleaning, and chassis wash. Of the three, daily servicing accounts for the majority of staff time. On the average, servicing and cleaning in the American study accounted for 24 percent of maintenance labour-hours or about 111 hours per year. The coefficient of correlation between peak-hour vehicles and labour-hours for servicing and cleaning was 87 percent, leaving a standard error of 13 percent.

**Bus Inspections.** The inspection function generally consists of some type of inspection (e.g., safety, seasonal, minor, major, and statutory) and some amount of repair time, which is included in each inspection. On the average, inspections accounted for 17 percent of total maintenance manpower but varied significantly by transit property. The coefficient of correlation between inspection labour-hours and kilometers was only 20 percent. The primary reason for differences was local maintenance philosophy regarding inspection. Some properties devoted 50 percent of inspection time to running repair, whereas others allowed no running repairs during inspections. On the average transit properties required 78 labour-hours per year for each vehicle for inspection activities.

**Body Repairs.** The body subsystem is composed of running repair and major repair to body, painting, upholstery, and glass. Accidents are a significant factor driving body man-hour requirements. Agencies with lower accident rates naturally had lower body hours. On the average, the body subsystem accounts for 15 percent of total labour-hours. The amount of hours devoted to body repair is a function of vehicle kilometers (i.e., exposure), accident rates, and policy regarding acceptable vehicle appearance. On the average, transit agencies spent 71 hours for body repair per year. The coefficient of correlation between vehicle-kilometers and labour-hours required for body repair was 65 percent.

**Engine and Fuel.** The engine and fuel subsystem is made up of repair, removal and replacement, and rebuild times for all engine and fuel system components. Engine and fuel hours accounted for an average of 11 percent of maintenance labour-hours. The survey properties required about 51 labour-hours per vehicle per year on engine and fuel maintenance. The coefficient of correlation between engine and fuel labour-hours and vehicle-kilometers was 76 percent, leaving 24 percent not accounted for by distance. Most of this variation was accounted for by vehicle type. Depending on the vehicle type, labour-hours ranged from 40 to 70 per 52,000 kilometers. The remaining standard error may have been the result of mechanic training, facility efficiency, and contracting provisions.

**Braking Subsystem.** The braking subsystem is made up of running repair and reline work applied to the parking brake and the front and drive axles of revenue buses. On the average, braking labour-hours accounted for 9 percent of total maintenance costs. Actual braking hours averaged 40.0 per vehicle per year. The coefficient of correlation between braking hours and vehicle-kilometers was 75 percent. The primary factors driving differences between properties were kilometers of operation, route speed, and vehicle type. Although values were not available for terrain, as might be expected, properties with hilly terrain generally had values on the high side of the mean. Correspondingly, agencies with flat terrain generally had values on the low side. Other variables, including mechanic skill and training and facility and support equipment available, may also contribute to differences.

**Electrical Subsystem.** The electrical subsystem is made up of running repair, removal and replacement, and rebuild activities for starters, alternators and generators, batteries, and miscellaneous electrical components. Overall, electrical work accounted for 6.5 percent of total labour. Annual average work hours were 30.2 per 52,000 kilometers. Differences between transit properties was primarily attributable to kilometers and vehicle type, although climate may have had a minor impact. The coefficient of correlation between electrical labour-hours and vehicle-kilometers was 75 percent, but this rose to 95 percent when vehicle type was also evaluated. Both climate and speed were evaluated as potential independent variables but no significant correlation was found.

**Transmission.** The transmission is made up of running repair, removal and replacement, and rebuild work on the transmission and differential. Tearing down, cleaning, and rebuilding of small accessories are also included here. Overall, the transmission subsystem accounted for 5 percent of total maintenance labour-hours. About 24 labour-hours were spent each 50,000 kilometers and the coefficient of correlation was 77 percent. The difference between properties was a function of vehicle-kilometers, trans-mission type and vehicle speed. Mean transmission man-hour requirements ranged from an average of 36 per 50,000 kilometers for the V730 to 84 per 50,000 kilometers for the VH and VS transmissions.

**Suspension and Steering.** The suspension and steering subsystem is made up of running repair, removal and replacement, and rebuild activities for all primary components of these systems. Overall, this subsystem accounted for about 4 percent of maintenance costs. About 18 labour-hours were spent each 52,000 kilometers. The coefficient of correlation between labour-hours and vehicle-kilometers was 66 percent. Speed and climate did not appear to have an effect on the analysis. Steering and suspension hours are probably related to road conditions (e.g., potholes), although no numerical data were available to evaluate this factor.

**Wheels and Tires.** Many of the transit properties in the TRB survey contract for most of their tire work. Some of the properties only remove and replace tires, whereas others repair all failures occurring in the swing and night shifts and have the contractor repair those that can wait until the day shift. Wheels and tires accounted for about 3 percent of total maintenance labour-hours. On the averages, agencies that engaged in some wheel-and-tire repair reported about 16 labour-hours per 52,000 kilometers. The coefficient of variation between wheel-and-tire labour-hours and distance travelled was only 57 percent. Although the standard error is substantial, it was primarily a function of different contracting arrangements which could not be evaluated numerically.

**Cooling System.** The cooling function is made up of all maintenance activities on the vehicle's engine cooling subsystem. Overall, the cooling subsystem accounted for 3 percent of total manpower and averaged 12.0

labour-hours per 52,000 vehicle-kilometers for those properties with relatively mild summers. The primary cause of deviation between properties was the kilometers of operation, although summer climate also had a significant impact. The coefficient of correlation between the independent variables of vehicle-kilometers and climate to labour-hours was 75 percent. As expected, the agencies with moderate summer temperatures reported substantially lower labour-hour requirements than those with hot summers.

**Heating and Ventilation.** The air conditioning, heating, and ventilation subsystem is made up of running repair, removal and replacement, and rebuild activities on all applicable components. Overall, this subsystem accounted for 2 percent of maintenance costs. The two major factors causing differences between properties was vehicle-kilometers and climate. The coefficient of correlation between vehicle-kilometers and climate and labour-hours was 87 percent. Much of the remaining deviation could be attributed to policy, with some agencies accepting failures. The average for agencies with a cool and mild summer (i.e., those that generally operate without air conditioning) was 8.8 hours per 52,000 kilometers and this was the value that was used for this study for Canadian properties.

**Air System.** The air subsystem is made up of running repair, removal and replacement, and rebuild activities for all primary components related to the air system. Overall, this subsystem accounted for about 2 percent of maintenance costs. About 7 labour-hours were spent each 52,000 kilometers. The coefficient of correlation between labour-hours and vehicle-kilometers was 66 percent. Although the standard error is substantial, it was primarily a function of different accounting arrangements which could not be evaluated numerically.

## MAINTENANCE MEASURES

In addition to the preceding labour hour requirements, some additional maintenance measures could be derived from the Mississauga data as shown in Exhibit 12. These include mean time between defects (MTBD) and mean time to repair (MTTR). The total annual number of defects or incidents for each vehicle subsystem is also shown in the exhibit.

Aside from bus inspections, the most frequent defects or incidents are attributable to body repairs and the electrical system. The electrical system accounted for almost 20 percent of all reported defects, almost the same percentage as for body repairs. Of course, many of these items may be relatively minor such burned-out lamps and broken mirrors. Major items such as engine and transmission repairs have a much larger average mean time to repair but tend to occur much less frequently. The average mean time to repair for an engine or transmission defect is over three hours but is considerably less for many of the other subsystems.

*Exhibit 12*

***Some Maintenance Measures by Vehicle Subsystem***

| Vehicle Subsystem | MTBD (km) | MTTR (hr) | Annual Defects | | Annual Hours | |
|---|---|---|---|---|---|---|
| | | | Number | Percent | Number | Percent |
| Service/Cleaning | n/a | 0.20 | 534.7 | -- | 108.0 | 23.0% |
| Bus Inspections | n/a | 1.85 | 40.1 | 20.6% | 74.2 | 15.8% |
| Body Repairs | 1,400 | 1.76 | 37.3 | 19.2% | 66.0 | 14.1% |
| Engine and Fuel | 3,500 | 3.40 | 14.9 | 7.7% | 50.7 | 10.8% |
| Braking System | 3,000 | 2.40 | 17.2 | 8.8% | 41.4 | 8.8% |
| Electrical System | 1,500 | 0.95 | 35.6 | 18.3% | 33.8 | 7.2% |
| Transmission | 6,200 | 3.25 | 8.4 | 4.3% | 27.4 | 5.8% |
| Suspension/Steering | 3,500 | 1.36 | 14.9 | 7.7% | 20.3 | 4.3% |
| Wheels and Tires | 8,200 | 2.25 | 6.4 | 3.3% | 14.3 | 3.1% |
| Cooling System | 7,200 | 1.93 | 7.3 | 3.8% | 14.0 | 3.0% |
| Heat/Ventilation | 9,400 | 1.78 | 5.5 | 2.8% | 9.9 | 2.1% |
| Air System | 7,600 | 1.40 | 6.8 | 3.5% | 9.5 | 2.0% |
| TOTAL | | | 194.4* | 100.0% | 469.5 | 100.0% |

* excluding service/cleaning

## TOTAL MAINTENANCE COSTS

The cost of maintenance is the total of all costs incurred by an operator in securing that an asset, such as a vehicle, is maintained in operation at an acceptable standard of economical operating performance over its useful life. It comprises: the provision of equipment for servicing, repair and overhaul; the land and buildings for workshops and their maintenance premises; spare parts and components; the cost of people directly employed; administrative overheads; and payment for contracted services.

The costs of maintaining a bus are difficult to establish, because virtually every transit system has a different basis for allocating costs. In an effort to determine maintenance costs, models were developed using industry averages, modified where appropriate by local estimates, and refined whenever possible by validated data.

Information available from the annual CUTA Fact Book (20) indicates that vehicle maintenance expense for all modes of transit is around $316 million a year. Since total vehicles are approximately 13 thousand, the maintenance cost per vehicle is around $26,000 per year. Since this includes both rail vehicles and buses, it is anticipated that rail vehicles would be higher and buses would be lower than this average figure.

Using other figures in the CUTA Fact Book, it is determined that the average kilometers travelled per vehicle per year is 52,000 and that the vehicle maintenance is 19 percent of the total cost of operations per kilometer of $2.37 or $0.46 per kilometer. Applying this figure to a bus operating 52,000 kilometers a year yields the following value:

**Annual Maintenance Cost = $24,000 Per Year.**

## MAINTENANCE COST BREAKDOWN

As an integral part of this study, a survey of transit properties was conducted to: (1) collect data which described the incidence and costs of repair/failure by type of event, (2) collect information on the existing maintenance, information management and operational practices and analysis systems that are relevant to diagnostic systems, and (3) collect data on the operating and maintenance requirements of diagnostic systems.

The information and material was collected through the use of telephone interviews with a representative sample of Canadian transit properties. The survey procedure was as follows:

1. survey design and client approval,
2. telephone contact with candidate properties,
3. follow-up letter detailing data and information needs,
4. data summary and request for any additional data,
5. preparation of a technical memo.

The criteria for selecting the properties for the survey was based on assuring a representative sampling of the variety of fleet sizes and geographical locations. The properties included: Edmonton, Ottawa, Halifax/Dartmouth, Quebec City, Hull, Toronto, Kitchener/Waterloo, Winnipeg, Mississauga, Vancouver, Montreal, Victoria, North Bay.

### Availability of Basic Data

In approaching the properties during the survey, the team attempted to obtain as much quantitative data as possible which characterized the costs of vehicle maintenance. This data was then used to compare with the previously-developed industry averages. The industry averages were subsequently modified where appropriate, and refined whenever possible by the validated local data. This data could then to be used to provide some preliminary estimates of the potential cost savings possible with automated systems.

The study team found that while most properties had or were in the process of installing computerized vehicle maintenance information systems, only two of the properties had their data disaggregated by vehicle component subsystem and/or cause. Further, there was apparently no data available which segmented the planned and unplanned maintenance items. The closest form of this data was obtained from an analysis of the in-service repair logs (roadcalls) which were available from some of the surveyed properties.

Of the survey participants, it was found that all properties have some form of systematic maintenance costing and preventive scheduling system in place now. Three properties were in the process of computerizing their data system while all the large properties had mature data information system in place for a number of years.

The data for each fleet is classified in a distinct way with virtually no common data storage or reporting conventions between the properties. With the exception of the common maintenance data reported to the Canadian Urban Transit Association, which is highly aggregated, the lack of a uniform repair classification procedure makes comparisons between systems difficult. This fact posed severe restrictions on the amount of pooled data that was available. The study thus uses example data, usually from one property, and has not been able to ensure consistent definitions and categorizations between data sets.

### Maintenance Cost Comparisons

From the data on annual maintenance cost supplied to the study team from a number of properties, two properties that appeared to have the most detail and the most reliable costs were selected for detailed analysis. The annual maintenance cost by subsystem and category for Mississauga and Victoria are shown in Exhibit 13.

*Exhibit 13*

***Comparison of Victoria and Mississauga Maintenance Costs***

| Vehicle | Labour | | Parts | | Total | |
|---|---|---|---|---|---|---|
| Subsystem | Victoria | Miss'ga | Victoria | Miss'ga | Victoria | Miss'ga |
| Service/Cleaning | $5,710 | $4,320 | $ 0 | $ 0 | $5,710 | $4,320 |
| Bus Inspections | 1,720 | 2,970 | 0 | 100 | 1,720 | 3,070 |
| Body Repairs | 1,880 | 2,640 | 480 | 850 | 2,360 | 3,490 |
| Engine and Fuel* | 3,070 | 2,030 | 1,310 | 380 | 4,380 | 2,410 |
| Braking System** | 2,960 | 1,660 | 1,040 | 1,580 | 4,000 | 3,240 |
| Electrical System | 1,480 | 1,350 | 430 | 960 | 1,910 | 2,310 |
| Transmission | 1,590 | 1,100 | 1,140 | 900 | 2,730 | 2,000 |
| Suspension/Steering | 440 | 810 | 390 | 450 | 830 | 1,260 |
| Wheels and Tires | 1,300 | 570 | 0 | 90 | 1,300 | 660 |
| Cooling System | --- | 560 | --- | 400 | --- | 960 |
| Heat/Ventilation | --- | 400 | --- | 420 | --- | 820 |
| Air System | --- | 380 | --- | 540 | --- | 920 |
| TOTAL | 20,150 | 18,790 | 4,790 | 6,670 | 24,940 | 25,460 |

* includes heating and cooling for Victoria
** includes air system for Victoria

It should be noted that these costs are indicative only and are based on a small sample of equipment. The costs do, however, correlate very well with the industry averages by subsystem reported in the American study and the final total annual maintenance cost correlates very well with the industry wide averages in the CUTA fact book. Based on these results, it was decided that the maintenance cost data from Mississauga could be used with considerable confidence as being representative of the maintenance operations of most transit properties in Canada.

## Representative Maintenance Costs

Based on in-depth analysis of data from several transit properties across Canada, it was concluded that data from the Mississauga Transit System was representative of other operations in Canada since the data correlated very well with industry-wide averages in both Canada and the United States. The maintenance cost figures for parts and labour by vehicle subsystem provided in Exhibit 14 were therefore chosen for utilization in any cost-benefit or cost-effectiveness evaluation of vehicle diagnostic systems for urban buses.

*Exhibit 14*

***Maintenance Hours and Costs by Vehicle Subsystem***

| Vehicle Subsystem | HOURS | | COSTS | | | % of Total |
|---|---|---|---|---|---|---|
| | Number | Percent | Labour | Parts | Total | |
| Service/Cleaning | 108.0 | 23.0% | $4,320 | $ 0 | $4,320 | 17.0% |
| Bus Inspections | 74.2 | 15.8% | 2,970 | 100 | 3,070 | 12.1% |
| Body Repairs | 66.0 | 14.1% | 2,640 | 850 | 3,490 | 13.7% |
| Engine and Fuel | 50.7 | 10.8% | 2,030 | 380 | 2,410 | 9.5% |
| Braking System | 41.4 | 8.8% | 1,660 | 1,580 | 3,240 | 12.7% |
| Electrical System | 33.8 | 7.2% | 1,350 | 960 | 2,310 | 9.1% |
| Transmission | 27.4 | 5.8% | 1,100 | 900 | 2,000 | 7.8% |
| Suspension/Steering | 20.3 | 4.3% | 810 | 450 | 1,260 | 4.9% |
| Wheels and Tires | 14.3 | 3.1% | 570 | 90 | 660 | 2.6% |
| Cooling System | 14.0 | 3.0% | 560 | 400 | 960 | 3.8% |
| Heat/Ventilation | 9.9 | 2.1% | 400 | 420 | 820 | 3.2% |
| Air System | 9.5 | 2.0% | 380 | 540 | 920 | 3.6% |
| TOTAL | 469.5 | 100.0% | 18,790 | 6,670 | 25,460 | 100.0% |

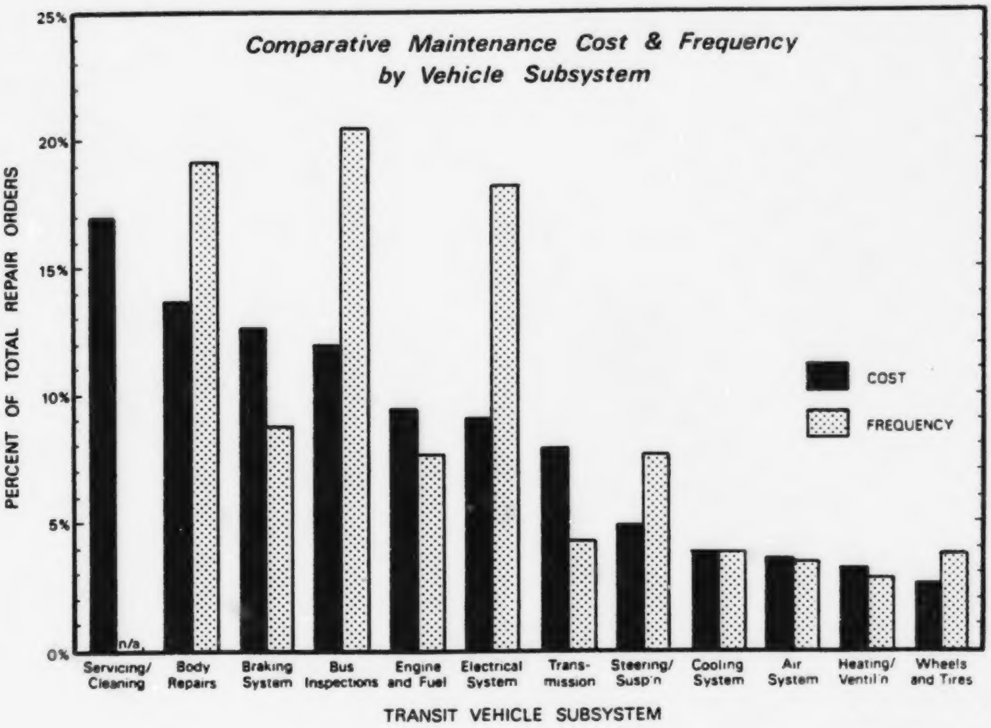
It should be noted that these maintenance cost figures also include the cost of in-service breakdowns within the appropriate subsystem (except for the cost of lost revenue and riders dissatisfaction with the service).

The survey attempted to assemble a profile of the most common causes of in-service breakdowns and repairs. Data was obtained from two properties -- London and Victoria. The data indicated that the large majority of calls are for small problems with the top five most frequent causes being: signals, overheating, brake lights, heating, doors. A very low percentage of the problems are seen as amenable to early diagnosis.

In discussions with the managers, the study team attempted to determine if there were any data on the marginal cost of in-service breakdowns. No properties had estimates of the impact and all believed the costs to be relatively small. They saw in-service problems, however, as one of the most frequent source of customer complaints and thus a 'visibility' problem. Although there is problem resulting from lost revenue and customer dissatisfaction, the secondary effects of roadcalls or in-service breakdowns were not analyzed in this study so that the anticipated benefits of vehicle diagnostic systems would not be overstated.

The representative maintenance cost figures by vehicle subsystem are also illustrated in Exhibit 15 along with the frequency of occurrence of the defects or repairs. As shown, the largest maintenance cost items are servicing/cleaning and body repairs which are not particularly amenable to diagnostic systems. Braking systems, inspections, engine and fuel, electrical systems and transmissions, however, are also heavy cost items that are well-suited to diagnostic aids.

*Exhibit 15*



# Section 2:

# DIAGNOSTICS

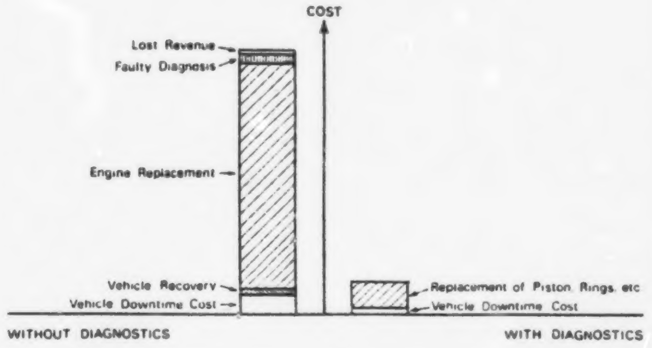
# 5. DIAGNOSTIC FUNCTIONS

Transit vehicle maintenance costs are about $24,000 per vehicle per year. As maintenance costs have grown, so has interest in ways of reducing them while enhancing the availability of vehicles for service. One potential way of attacking both problems is to use diagnostic systems to lower the cost of maintaining transit equipment and to reduce downtime. Many such diagnostic aids have been developed or proposed.

As an example of the way in which diagnostic systems reduce maintenance costs, consider the results of some tests on London Regional Transport buses (20). Undoubtedly, the most dramatic events occurred in relation to engine monitoring as illustrated in Exhibit 16. With immediate warning of faults such as piston ring failures and the measures of relative cylinder performance, the need for engine replacement from compression failure will be reduced. Conservative estimates indicate that replacement of a single piston and ring assembly typically costs about a tenth as much as an engine overhaul.

*Exhibit 16*

***Comparative Costs - Engine Compression Failure***



Any consideration of diagnostic systems for urban transit vehicles is based on two assumptions: first, that current vehicle maintenance practices embody a number of problems that cause maintenance costs to be higher than necessary, and second, that diagnostic systems perform functions that can reduce or eliminate these problems.

## MAINTENANCE PROBLEMS

Maintenance problems are of two general types -- those that increase the frequency of maintenance actions and those that increase the cost of each action. Manufacturing faults, improper operation/neglect, and maintenance-induced faults contribute to the frequency of maintenance; inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity contribute to the cost of maintenance. These problems is described in the following paragraphs.

**Manufacturing faults** are defects that result from improper manufacture or assembly of new or rebuilt vehicles or parts, or from inadequate preparations for storage or removal from storage. Manufacturing faults increase the frequency of maintenance actions, and include such defects as bad filters or seals, loose or missing fasteners, poorly machined parts, and incorrect wiring.

**Improper operation/neglect** is any improper operation of the vehicle or neglect of critical checks by the operator or crew and also increases the frequency of maintenance. Typical abuses are operating the vehicle, engine, or transmission at excessive speeds or temperatures, and riding the brake. Examples of negligence are operating the vehicle with improper levels of oil, coolant, or electrolyte, or operating it with the emergency brake set.

**Maintenance-induced faults** are defects caused during maintenance. Such faults increase the frequency of maintenance. Examples are reversed electrical polarity, mechanical damage to parts, or failure to replace drain plugs when replacing oil or coolant.

**Inefficient fault isolation** is the use or improper procedures or test equipment, or poorly trained personnel, resulting in excessive time to locate and isolate faults. Since only time (not parts) is involved in fault isolation, the effect of inefficient fault isolation is to increase the labour expended in maintenance actions.

**Faulty malfunction diagnosis** is the incorrect diagnosis of a malfunction involving the replacement of good parts, and results from the often-used procedure of trial-and-error replacement. The impact of faulty malfunction diagnosis is on both parts and labour costs. Examples are replacing a battery when the malfunction is in the generator, replacing spark plugs or the carburetor when the timing is bad, or replacing the radiator when only the thermostat is bad.

**Late detection** is the failure to detect a fault, which becomes worse over time and/or causes secondary faults. Late detection affects both parts and labour costs and can necessitate more extensive maintenance than if the fault had been detected in its early stages. Examples are a failing generator which damages the electrical system, worn brake linings which lead to scoring of the brake drums, or a clogged air filter which allows dust ingestion to damage the engine.

**Excessive rework** is the need for additional maintenance caused by an improper initial repair. The impact of excessive rework is on both parts and labour costs. Examples are adjusting the timing to incorrect specifications, installing a brake wheel cylinder improperly allowing brake fluid to leak, etc.

**Low productivity** affects only labour costs and occurs when any maintenance action takes longer than necessary. Examples are taking excessive time to road test or to install and test parts.

These general problems, although they include the major contributors, may not cover every possible influence on maintenance frequency and costs.

## DIAGNOSTIC FUNCTIONS

After the problems inherent within the maintenance system are identified, it becomes necessary to determine what diagnostic functions are possible and how they might affect the problems. Particular diagnostic aid systems that could perform the functions are not defined. General definitions of the diagnostic functions are provided below:

**Use monitoring** allows observations of the ways that the vehicle is operated. It records vehicle/driver and vehicle/environment interactions (hours of operation, number of starts and stops, excessive speeds or temperatures, etc.). Results provide information on vehicle duty cycles and on improper operation/neglect.

**Health monitoring** allows observation of the basic performance or soundness of critical components or subsystems of the vehicle. It might be used to check vehicles prior to dispatch and to detect any manufacturing faults.

**Failure prediction** permits the measurement of subsystem or component use, and estimates its useful life remaining before maintenance is required. Failure prediction estimates reliability so that maintenance can be performed before faults occur or before secondary faults result.

**Failure detection** indicates whether the vehicle should be driven by displaying warnings of dangerous conditions such as low fluid levels or clogged filters. It could also be used to trigger maintenance before faults occur or cause secondary faults.

**Fault isolation** provides faster and more accurate identification of faults by locating and isolating the component causing the malfunction, reducing the chances of replacing the wrong part and time spent locating faults.

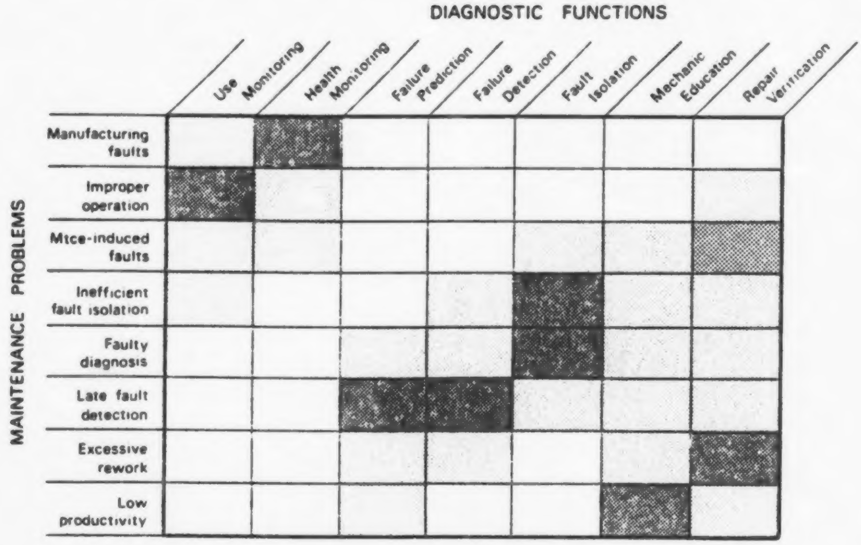
**Mechanic education** provides training to increase the capability and efficiency of the mechanic, reducing maintenance time.

**Repair verification** checks that proper maintenance and repair have been correctly performed, reducing the number of jobs that must be redone and detecting any additional faults caused by maintenance actions.

Each of these diagnostic functions is capable of reducing the severity of one or more maintenance problems. For example, the fault isolation function has an impact on two problems: it enables procedures for fault isolation to be performed more efficiently and also indicates which components require either repair or replacement, thus reducing faulty malfunction diagnosis. Repair verification indicates if faults requiring remedial action have been properly corrected, assuring that no rework is necessary. A summary of the assumed interactions is shown below.

Exhibit 17

*Diagnostic Problem-Function Interactions*



DIAGNOSTIC FUNCTIONS

MAINTENANCE PROBLEMS

| | Use Monitoring | Health Monitoring | Failure Prediction | Failure Detection | Fault Isolation | Mechanic Education | Repair Verification |
|---|---|---|---|---|---|---|---|
| Manufacturing faults | | ■ | | | | | |
| Improper operation | ■ | | | | | | |
| Mtce-induced faults | | | | | | | ▨ |
| Inefficient fault isolation | | | | | ■ | | |
| Faulty diagnosis | | | | | ■ | | |
| Late fault detection | | | ■ | ■ | | | |
| Excessive rework | | | | | | | ■ |
| Low productivity | | | | | | ■ | |

As seen, some maintenance problems contribute to degree of reliability or frequency of unscheduled maintenance, and some contribute to level of maintainability, or amount of resources required by unscheduled maintenance. The resources used in a repair action may be affected by any or all of the following maintenance problems: inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity.

Frequency of repair is influenced by three of the problems: manufacturing faults, improper operation/neglect, and maintenance-induced faults form both scheduled maintenance actions and previous unscheduled actions (the more often maintenance is performed, the greater the possibility that a maintenance-induced fault will result).

Diagnostic systems have a number of functions from on-board health monitoring to off-board fault isolation and repair verification -- all intended to either reduce current maintenance problems and costs or to increase reliability. In the next chapter, some of the transit vehicle operating parameters that can be monitored with diagnostic systems will be discussed.

# 6. DIAGNOSTIC PARAMETERS

The required technology is available for on-board vehicular diagnostic systems on surface transit systems. These systems have immediate economic benefits in terms of reduced incidence of downtime, reduced maintenance cost, and improved fuel economy. Operators of public transportation systems have recognized these benefits and are now making use of automatic vehicle monitoring systems and off-board diagnostic systems to improve their service.

The vehicle monitoring systems consist of vehicle location and status monitoring plus digital and voice communications systems and central monitoring and control systems. Off-board diagnostic systems include oil analyzers, electronic fuel injection diagnostic systems, and diesel engine diagnostic systems.

The proliferation of microcomputer-based engine control systems and the growing use of electronic dash panel displays in passenger cars and trucks has led transit operators to consider their use. Such instrumentation can offer a number of potential benefits to the transit operator, but a system capable of performing all the required functions would necessarily be complex. Moreover, the driver aid functions imply on-board data processing and display, while the maintenance-aid features imply on-board recording and off-board post-trip analysis.

Transit vehicles are usually highly customized to the operator's requirements. Not every operator would require or desire all the possible data acquisition systems. At the same time, a system capable of being customized at the individual sensor level would be so flexible as to be cumbersome and costly. One solution would be a core-system design.

## DIAGNOSTIC PARAMETERS

A core-system design would be one which had attributes that every transit vehicle needs and modular building blocks for the remainder of the sensors (see table below). A useful rationale for modularizing the sensors organizes them so that each module adds a specific kind of diagnostic capability. For example, this could include an engine diagnostics module, a transmission diagnostics module, and a braking system module.

*Parameters for Vehicle Diagnostics*

*Exhibit 18*

| Basic package | Additional package |
|---|---|
| Engine rpm | Total accumulated engine revolutions |
| Road speed | Oil level |
| Accumulated mileage (odometer) | Oil temperature |
| Air pressure (brakes) | Crankshaft timing pulse |
| Fuel level | Turbocharger temperature |
| Fuel flow | Air filter differential pressure |
| Oil pressure | Belt-break sensors |
| Coolant level | Electrical currents (waveforms) |
| Coolant temperature | Tire pressure and location |
| Exhaust temperature | Diesel injector pressure waveforms |
| Battery voltage | |
| Time (date) | |

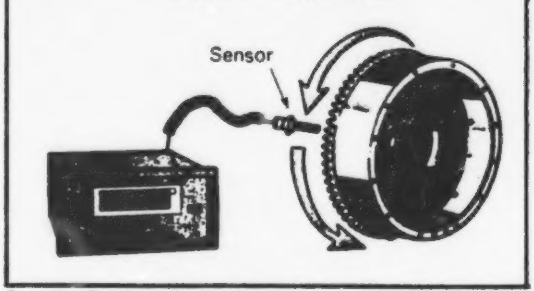
The problem of instrument panel clutter can be solved by adapting the new digital displays available for passenger car use. The driver can call up seldom used parameters on this display or they can be brought up automatically under alarm conditions by the on-board microcomputer.

In addition to performance requirements in the rugged transit environment, sensors for the basic parameters must meet certain standards due to the long life of the transit vehicles. First, the sensors must have a bounded accuracy, that is they must not drift indefinitely in a single direction, and during their useful life their uncertainties must lie within definite limits. Second, they must perform without provision for recalibration. Third, all sensors for a given parameter must conform closely to a transfer function norm from unit to unit so that replacement of a defective sensor is only a matter of mounting and connecting the new unit.

**Speed and rpm sensors** - Engine RPM and wheel speed are important parameters for transit vehicles. Besides providing protection against engine overspeed, RPM data are used to determine power peaks and the best shift points for maximum acceleration. Both the actual speed and accumulated kilometrage of the vehicle are inferred from the wheel speed

*Exhibit 19*

***Digital Tachometer***



Source: Cummins Engine Company

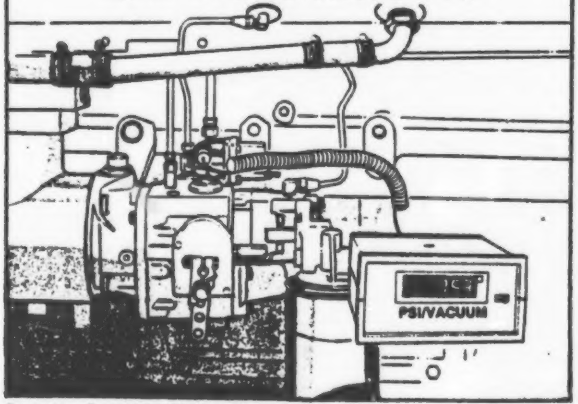
parameter. The engine RPM data is a common measure of engine operating speed and is critical to performance. Accurate measurement of RPM is critical to engine diagnostics.

The most common methods for measuring RPM are the electric tachometer and the digital tach. Both are electric and use a sending unit mounted in the flywheel housing. With the electric tachometer, a single pole ring gear sensor is used (a magnetic reluctance sensor that detects sudden changes in reluctance such as those caused by steel protuberances on a rotating shaft). It measures the frequency of the gear teeth rotating and displays this frequency as an RPM. A dual pole ring gear sensor can also be used. It would measure the time it takes for each ring gear tooth to pass from pole 'A' to pole 'B'. The time interval would be used to calculate the RPM.

**Air pressure** - The air pressure in the primary and secondary brake reservoirs is the highest priority safety parameter included in the proposed basic diagnostic module. Measurement of this parameter permits detection of either a moderate air leak ar a sudden failure in the power supply for the braking system. The conventional solution for a direct reading gauge has been to mount a Bourdon tube dial gauge where it is visible to the driver, and to pipe it back to the air reservoir. Some attempts have been made to drive a rotary potentiometer with the Bourdon tube to obtain an electrical signal. The trend in diagnostic systems is toward an all-electrical display.

*Exhibit 20*

***Digital Pressure/Vacuum Gauge***



Source: Cummins Engine Company

Recently, to monitor pressure and vacuum in all of the engine systems (intake-manifold pressure, fuel vacuum, blowby, air-filter restriction, etc.), digital pressure/vacuum gauges have been used. A sending unit measures the pressure/vacuum and sends a corresponding voltage to the gauge. The digital gauge converts the voltage into a specific pressure/vacuum reading. The pressure sensor (sending unit) is a capacitive pressure sensor

## *On-Board Sensors for Transit Vehicles*

*Exhibit 21*

| PARAMETER | SENSOR | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| **Speed and rpms** | Hall-effect sensor | Common proximity sensor | Preamplification necessary to obtain good signal to noise ratio |
| | Wiegand effect sensor | Large output signal, relatively constant as function of speed | Sensitivity not very great, except at threshold level |
| | Magnet-reedswitch sensors | Simple, self-contained, fairly inexpensive | Temperature dependent, intermittent reliability |
| | Reluctance sensors | Excellent signal to noise ratio, self-powered and self-contained | Output signal increases with the shaft speed |
| **Air pressure** | Aneroid/LVDT pressure | Outputs an AC voltage proportional to gauge pressure | Requires fairly complex electronics in conjunction |
| | Diaphragm/rheostat sensor | Low cost, high level ouput | Hysteresis due to moving parts as well as wear |
| | Capacitive pressure sensor | Very good accuracy, relatively insensitive to temperature | Only recent economical mass production techniques |
| **Oil pressure** | Similar to air pressure but requires a higher temperature tolerance | | |
| **Coolant level** | Capacitance level sensor | Very high response time | Requires highly regulated power, no transient voltage protection |
| | Ground circuit level sensor | Simple, low-cost, very fast response time | Must be resistant to corrosion |
| | Float/reedswitch level sensor | Proven device on passenger cars | Requires modification to meet rugged transit environment |
| **Coolant temperature** | Thermistor-type sensor | Good sensitivity, accuracy and stability | Highly nonlinear negative exponential characteristic |
| | Platinum-film resistance | Good performance and long-term stability | Sensitivity is not very great, signal requires amplification |
| | Nickel resistance sensors | Very simple; moderate, level, nearly linear, output | Poor accuracy |
| **Oil temperature** | Similar to coolant temperature sensors | | |
| **Exhaust gas temperature** | Thermocouple type sensor | Capable of measuring very high temperatures | Signal produced requires conditioning |
| | Thermistor type sensor | High sensitivity | Limited low-end temperature range; highly nonlinear output |
| | Bimetal/potentiometer | Nearly linear output, stable and accurate | Slow response time |
| | Platinum resistor sensor | Large temperature range, linear output, stability | High cost, slow response time, low sensitivity, amplification |
| **Fuel level** | Float/rheostat sensors | Simple and inexpensive | Nonlinear output, and poor accuracy |
| | Capacitance sensors | No moving parts, accurate electrical output | Requires regularly-shaped fuel tank |
| **Fuel flow rate** | Turbine flowmeter | Standard flow measurement concept | Accuracy is sensitive to fuel temperature and composition |
| | Ball-in-race flowmeter | Used in gasoline engines | Accuracy strongly affected by fuel viscosity |
| | Positive displacement | Excellent performance as test sensors | Expensive |
| | Four-orifice flowmeter | Good performance as test sensor | Requires high performance pump and sensitive pressure sensor |

In one approach to measuring pressure, the sensor is circular and composed of an alumina diaprahgm bonded to a thicker alumina substrate to form the capacitive plates. When pressure is applied, it deflects toward the substrate, causing an increase in capacitance (21). The voltage output is proportional to the pressure. The sensor has very good accuracy, a fast response time and is relatively insensitive to temperature.

**Oil pressure** - The oil pressure is the most important monitoring parameter to be measured on an engine. Maintaining the required minimum oil pressure, which is rpm dependent, is very critical for safe operation. At any engine rpm and road speed, the driver must be immediately informed of low oil pressure. This requirement implies the use of a continuous oil pressure sensor rather than a pressure switch.

The concepts used in oil pressure sensors are similar to those used in air pressure sensing, although oil pressure sensors require a higher temperature range because the sensor is mounted directly on the engine block.

**Coolant level** - The coolant level is another high priority parameter to be measured in a transit vehicle. A coolant temperature sensor can detect overheating caused by low coolant levels. In the case where a fast loss of coolant occurs, as when a hose ruptures, only a coolant level indicator will warn the driver before damage from overheating occurs. This does not call for high accuracy but requires a fast sensor response time.

The float/reedswitch sensor was originally developed for passenger car applications and would require modifications to be rugged enough for the much longer lifetime and rigorous environment of transit vehicles. The reedswitch in this sensor is operated by a float/magnet assembly. The ground circuit level sensor utilizes the electrical conductivity of the engine coolant. A probe immersed in the coolant receives an ac signal transmitted through the coolant and returns the signal to ground. The sensor has a fast response time and is a simple, low cost device which resists corrosion.

**Coolant temperature** - The coolant temperature sensor in a bus is called upon to provide a moderate accuracy (+ 1°C) and to survive in a severe environment. Digital gauges are used in which a sending unit measures the temperature and sends a corresponding voltage to the gauge. The digital gauge converts this voltage into a specific value. The digital gauge responds quickly to temperature changes and is very accurate.

The sending unit can be of several types. The nickel resistance sensor is the simplest with no more than a fine pure nickel wire wound on an insulating bobbin and suitably encapsulated. It provides a moderate level output which is nearly linear. The platinum-film resistance sensor shows the best performance and long term stability but the sensitivity is low. Thermistor-type and thermocouple-type sensors are also used.

**Exhaust gas temperature** - Particularly in turbocharged engines, fuel overloading is just as destructive to diesel engine life as dirty oil or too little coolant. The exhaust gas temperature sensor will produce a precursor signal which leads the rise in cylinder, head, piston, and valve temperatures, warning the driver and maintenance people of problems.

High temperature thermocouple sensors are capable of measuring at temperatures higher than engines can produce. The effective response time of this sensor depends on the type of junction mounting used and the exhaust gas flow rate. An exposed junction gives the fastest response time but requires special treatment to survive in the corrosive environment.

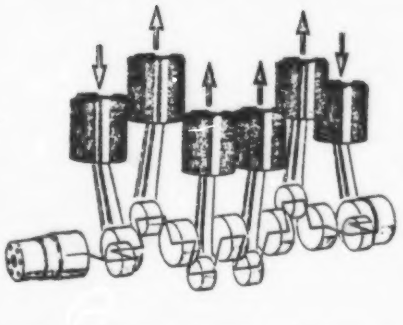
**Fuel level** - The fuel level parameter is used to determine the approximate volume of fuel left in the tank. This can be done with a capacitance level sensor. The capacitance sensor consists of a probe and a monitor module. When air displaces the fuel around the probe, it produces a change in electrical capacitance which is compared within the unit to a threshold value, resulting in a high-low electrical current output. The sensor has a very high response time but the version in production requires highly regulated power because no transient overvoltage protection exists within the unit. Other float/rheostat sensors are simpler and less expensive but provide poor accuracy.

**Fuel flow rate** - Accurate measurement of the fuel flow rate is essential to a real time computation of economy, but in buses, special problems are encountered. The fuel supply for the injectors is used for cooling the injectors as well as fueling the engine, thus return flow fuel systems are employed. Under most conditions, only a small fraction of the total fuel flow is net flow to the engine. A solution that could measure the net flow is complex and expensive.

**Cycle Event** - The last parameter required is the cycle event. The cycle event sensor permits the monitoring of the function of each cylinder while the engine is running. The cycle event sensor is mounted in the rocker lever cover and is placed over one of the intake levers. It sends a signal to a computer when that lever operates. By indicating to the computer which cylinder is being monitored, the computer will know when the cylinder fires. Since the computer knows the firing order, the functions of the other cylinders can also be monitored.

Exhibit 22

*Cycle Event Sensor*



Source: Cummins Engine Company

The cycle event sensor is similar to the flywheel ring gear sensor but it has only one pole. When the intake valve is closed, the magnetic field is not in contact with the adjusting screw. When the valve starts to open, the adjusting screw comes in contact with the magnetic field, sending a signal to the computer.

Of all the various sensors required for the basic module of an on-board diagnostics system, reasonably satisfactory solutions are available for all except the fuel flow rate (21).

# 7. DIAGNOSTIC SYSTEMS

Demonstrations are currently underway in several transit properties to develop systems that will enable microprocessors collecting information on-board vehicles to be in communication with a centralized operations centre and thus permit a better monitoring of vehicle location and status. Although these systems have been developed primarily to improve service, security and real-time information to users, they have also opened a path for reducing major vehicle breakdowns.

In a few of these demonstrations, for example, the on-board microprocessor has been linked with certain engine and component warning signals. This allows specific functions to be monitored from the operations centre, permitting an earlier identification of potential problems, and facilitating a preventive response before the vehicle actually breaks down. In essence, these systems create a simple bus diagnostic system. More importantly, linking the various components in this way lays the groundwork for more elaborate systems that will improve vehicle maintenance even further by monitoring an increasing variety of vehicle components, and eventually by tracking the actual health of the specific vehicle. This will be feasible since the information collected can be stored and used in the system's on-going preventive maintenance activities.

Operators of public transit systems have also recognized the benefits of off-board diagnostic systems to improve their service. Off-board diagnostic systems include oil analyzers, electronic fuel injection diagnostic systems, and diesel engine diagnostic systems. Harris Corporation introduced a computerized electronic device for automated engine inspection and fault isolation in 1977. Cummins Engine Company introduced a diesel engine diagnostic tool called Compuchek in 1981. And United Technologies developed and tested a prototype of an automatic bus diagnostic system in 1985 which combines a three-minute screening test at the fuel island with a 20-minute maintenance diagnostic test.

But transit is only one segment of the transportation industry which has expressed an interest in diagnostics. Just about every mode (rail, air, automobile, trucking, and, even, marine) has investigated or applied diagnostic systems. One of the more familiar experiments is the one at General Electric where a computer trouble-shooting system for use on their diesel electric locomotives is being introduced with built-in artificial intelligence and the capability of calling up displays of drawings, photographs or films of the various locomotive components.

The proliferation of microcomputer-based engine control systems and the growing use of electronic dash panel displays in passenger cars and trucks has led transit operators to consider their use. Such instrumentation can offer a number of potential benefits to the transit operator, such as:

- rapidly alerting the driver to unsafe or equipment-damaging conditions,
- providing pre-trip checkout to minimize on-the-road downtime,
- recording transient malfunctions or out-of-tolerance conditions for post-trip analysis,
- improving the efficiency of maintenance personnel through computer-aided fault identification,
- supplying management information for improved trip scheduling and full vehicle utilization, thus replacing tachograph instrumentation.

## EXISTING DIAGNOSTIC SYSTEMS

The purpose of this chapter is to provide an inventory and assessment of the state-of-the-art of vehicle diagnostic systems, including (1) on-board on-line, (2) on-board off-line, and (3) off-board off-line systems.

This review of the state-of-the-art included the following aspects:

- a review of relevant literature;
- a review of existing diagnostic systems currently used by Canadian transit properties;
- a review of diagnostic systems used in other industries (e.g. automobile, trucking) and in other countries (e.g. U.S.A., Japan, Europe);
- a review of selected manufacturers' products (e.g. Cummins Engine Company, United Technologies, General Motors Corporation);
- an identification of possible expansions or upgrading of existing systems to include additional features and/or capabilities.

## ON-LINE ON-BOARD MONITORING

Real time on-board monitoring and reporting systems are relatively common in transit although monitoring is at an elementary level and no diagnosis activity is attempted. The system is usually piggybacked onto basic FM voice communication system -- separate frequency for data link. They are generally implemented for vehicle monitoring and security functions such as: vehicle location and time, run/route data/destination sign control/monitor, driver request to talk, farebox activity, silent alarm, and farebox tampering. Out-of-specification conditions for engine oil pressure, engine coolant temperature, air conditioning operation, and air brake system pressure may be transmitted as an alarm.

In North America, the Chicago Transit Authority was the first transit property to investigate automatic vehicle monitoring. It began a two-year demonstration project in March 1970 with 570 vehicles on the late-night owl services (60 routes) and 120 low-power electronic signpost transmitters placed at strategic locations. Winnipeg was the next city in North America to investigate vehicle monitoring. In 1973, Transport Canada's Transportation Development Agency (now the Transportation Development Centre) entered into an agreement with Winnipeg Transit to determine the degree of accuracy that a random vehicle monitoring system using triangulation might provide in an urban area. The accuracy was good but the cost was prohibitive. About the same time, in January 1973, the Transportation Development Agency entered into a contract with B.C. Hydro in Vancouver to develop and test a vehicle location system using transponder devices coupled to receiving loops in the roadway. Ten roadside stations and 54 vehicles were equipped and tested over a two-year period but the cost of the receiving loops was too high in comparison to other technologies, and the system was dismantled after the demonstration. In Sudbury, also about the same time, a vehicle location system using roadside transmitters and manual polling of vehicles was developed. This system is still in use in Sudbury (22).

The Toronto Transit Commission also became involved with automatic vehicle monitoring in 1972 with the prototype development of its Communications and Information System (CIS). This system is based upon an odometer but the positional accuracy is calibrated by reference to signposts at the ends of routes, and also using an algorithm based upon doors opening and closing at known bus stops (similar to the SECAMA system in Paris). All of this enables vehicles to be located to an accuracy of within 12 meters at any time. Mississuaga Transit was also involved with vehicle monitoring systems, beginning in 1975.

The newest systems in Canada include Hull and Halifax. The Commission de Transport de la Communaute Regionale de l'Outaouais (CTCRO) in Hull has equipped all of its vehicles. The City of Halifax has developed a similar system for the Metro Transit Commission. Both cities used equipment supplied by Gandalf Data Limited of Ottawa and both cities have incorporated warning systems for out-of-specification conditions for certain mechanical conditions.

In the United States, after the initial system development work in Chicago by Motorola, the General Motors Transportation Systems Division began experimenting with automatic vehicle location on the Queen City Metro in Cincinnati using signpost transmitters augmented by odometer readings (this is the system that was moved to Windsor). In 1976, a demonstration began in Los Angeles that saw 200 vehicles equipped and 5,000 signposts erected for vehicle monitoring.

In 1958, in Europe, London Transport began experimenting with communication aids for bus monitoring and control. The first such system was BESI (Bus Electronic Scanning Indicator) which indicated to a central controller when a bus with a special plate on its side passed a series of roadside beacons. Later, in 1973, a more sophisticated system developed by the Marconi Company was tested. This was known as CARLA (Computer and Radio Location Aid) and represented a significant development in automatic vehicle monitoring systems. However, a reliance on voice radio channels limited its expansion and a new system, BUSCO (Bus Communication and Control System) using digital communications was introduced in 1983. This again was superceeded by Plessey Controls Limited Ident-a-Bus vehicle detection and AVM scheme in 1986. None of the systems incorporated mechanical condition warnings.

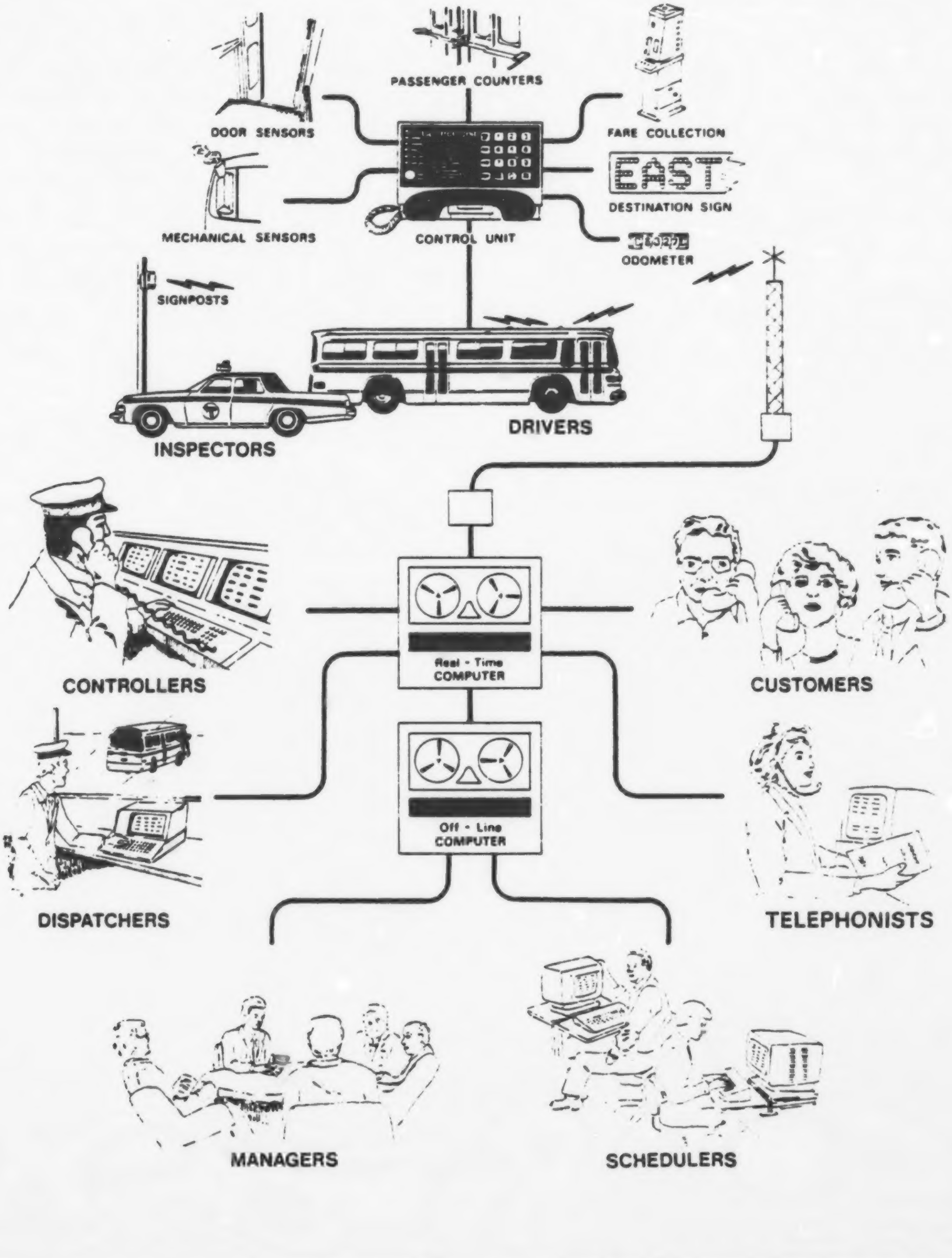
In Hamburg, in 1960, operation of a bus monitoring system similar to CARLA began operation, using roadside transmitters and on-board receivers. Between signposts, vehicle location information was augmented by odometer measurements. The Hamburg system eventually developed into a sophisticated control system. Other, similar systems have developed in Paris, Stockholm, Zurich and Milan. Stockholm, however, has virtually pulled out of AVM -- declaring it "too expensive and troublesome to keep in service" (23). Practically with exception, all city bus operators believe that AVM is a first-class operations management tool. But a good number doubt if it is worth the money.

In North America, Motorola and General Railway Signal are leading in real-time systems development in North America. Approximately 10 systems are in service: Toronto, Hull, Halifax, San Diego, Los Angeles, Chicago, Washington, Seattle, San Antonio, Omaha, Rochester. A number of other cities are in process of obtaining similar systems: Vancouver, Baltimore, Norfolk, Miami, Atlanta, West Palm Beach, Wilmington, Dallas, Fort Worth and Albequrque.

Complete systems automatic vehicle monitoring systems are relatively expensive. San Diego is expending $2.8 million for 300 buses which is approximately $1,000 per bus for on-board equipment.

*Exhibit 23*

*On-Board Vehicle Monitoring System*


PASSENGER COUNTERS
DOOR SENSORS
FARE COLLECTION
EAST
DESTINATION SIGN
MECHANICAL SENSORS
CONTROL UNIT
ODOMETER
SIGNPOSTS
DRIVERS
INSPECTORS
CONTROLLERS
Real - Time COMPUTER
CUSTOMERS
DISPATCHERS
Off - Line COMPUTER
TELEPHONISTS
MANAGERS
SCHEDULERS

## Alarm and Shutdown Systems

Alarm and shutdown systems aren't new, but electronic technological advancements have expanded the systems' value to most of the trucking industry (24) and several transit operators have incorporated aspects of these systems into their automatic vehicle monitoring systems.

The systems monitor parameters like coolant temperature, control engine-mounted devices, warn drivers of out-of-limit conditions such as low oil pressure, and shut down an engine to protect it from impending damage. The systems can monitor almost anything; the only limitations are cost and value to the user.

An example of a basic warning device is a probe inserted into the engine radiator to monitor coolant level. When the coolant level falls below the probe sensor in the radiator, an electrical signal is sent to a light mounted on the cab dash. This signal also can be connected to a second device to shut off engine fuel, usually after a predetermined delay. Probes or sensors also can monitor pressure, temperature and any on/off switch recognized by a computer. Sensors may include:

- oil level in the engine
- oil temperature
- coolant level in radiator
- turbo temperature
- RPMs
- coolant level or flow in engine
- lubricant level in the transmission or rear
- transmission or rear temperature
- hydraulic fluid level in fluid brake system
- air pressure in brake systems

Prices ranges from about $50 for a single-function system to about $750 for a multi-function system. The value of an alarm and shutdown system is the protection that it provides from driver abuse or inattention to equipment. Shutdowns are most often used because warning lights and alarms have often proved to be ineffective in fleet operations.

## Diagnostics in Aviation

The ultimate real-time diagnostic and reporting system is in use by the airlines. A system called 'BITE' (Built-In Test Equipment) is implemented by Air Transport Association (ATA) through ARINC, the ATA-sponsored industry communications firm, in which on-board microprocessors conduct a complete engine diagnosis by continuously monitoring key engine conditions such as: turbine inlet temperature, exhaust temperature, compressor and turbine speed, lube oil/fuel flows and pressures at various locations.

Data is transmitted to the ground maintenance base on command using discrete communications codes for each airline. The airborne crew is not even aware of the communications. The data is used to diagnose potential problems and engine and other equipment is changed out as the diagnostic system warrants sot that there is no in-frame overhauls and aircraft availability is maximized.

Airline-type diagnostic systems probably cannot be justified for use on urban transit buses since: on-board equipment costs are very high and the transit bus fleet is five times larger than air carrier fleet. The value of bus downtime costs are also low relative to transport class aircraft and there is no 'urgency' factor like in the airline industry to repair degraded engines or other components that no not affect service.

In the early 1970's, however, the United States Air Force began to evolve an approach to on-board systems which is tending to have applicability in the trucking and transit industry (25). This approach, known as the Digital Avionics Information System (DAIS), provides the following capabilities:

- Ability to modify an avionic system to meet new requirements primarily by means of software rather than hardware changes.
- Significantly greater total system mean time between failures through planned redundancy at subsystem, equipment and component levels.
- Greater flexibility in adding new sensors and systems to the system without rewiring the aircraft.
- An effective means of using modular or common avionic equipment in different types of aircraft.

In order to provide these capabilities, the Digital Avionics Information System consists of four basic elements:

- A set of sensors that provide input data.
- An information data buss that distributes informtion throughout the aircraft in a common format.
- An information processing system (micrcomputer) that performs data processing and storage.
- An information presentation, control, and actuation system that provides the required display and control signals.

By starting with the requirements of the total avionics systems and defining a family of standard sensors, data processing modules, memory modules, and actuator systems, it is possible to design a large number of different avionics systems with a minimum number of standard 'electronic building blocks'. In addition, it is possible to modify the system by adding a new sensor or adding data processing capability to an existing design without having to re-design the entire system. Finally, the field maintenance problem is greatly reduced since there are a smaller number of equipment and components to be stacked in repair centers. The cost of training of maintenance personnel is reduced for the same reason.

Although the nature of the sensors is different, the four basic elements of the DAIS system -- sensors, information data buss, data processing/ storage, and information presentation, control and actuation -- are identical to the elements required in an on-line on-board electronic diagnostic system for urban transit vehicles.

## OFF-LINE ON-BOARD MONITORING

On-board monitoring with bulk storage and off-line retrieval is a modernization/expansion of the very old mechanical tachograph device which is familiar to many transit properties.

### Electronic Tachographs

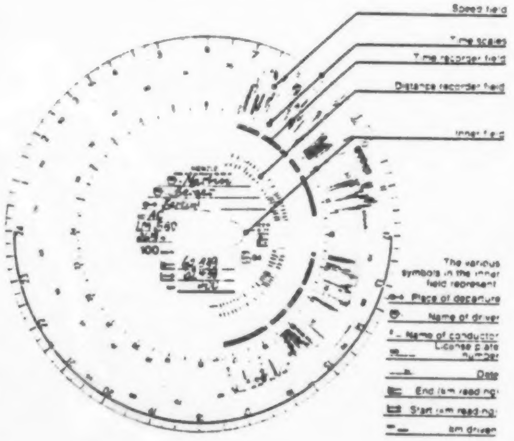
As early as 1939, a 'journey recorder', the forerunner of the tachograph, was mandatory for all passenger buses in Germany. Nine European countries now require tachographs to be installed on vehicles on many different kinds of trucks (depending on gross weight and type of load) and buses (except transit buses on scheduled routes).

There are a number of types of tachographs currently available, manufactured by Kienzle Argo, Veeder Root, Sangamo, Smiths, and VDO, which essentially operate in the same way. The tachograph is an instrument designed to indicate time, speed and distance and to record movement of the vehicle, speed travelled, distance covered and operation of the vehicle. The information is recorded on a special chart against a time scale by means of several styluses (needles). One stylus is utilized for each of the functions: speed, time and distance. Data analysis and reduction is performed manually.

The operation of the different types of tachographs is similar and straightforward. Prior to the start of a journey, a new circular recording disk is inserted into the tachograph. Once inserted, the disk begins to rotate and, so long as the clock continues to operate and the face of the tachograph remains closed, the styluses record by means of engraving traces on the chart surface information on the vehicle. Generally, the instrument is driven by a flexible drive shaft from the transmission gearbox connected through an adapter gearbox.

*Exhibit 24*

***Measuring Chart of a Tachograph***


Speed field
Time scales
Time recorder field
Distance recorder field
Inner field
The various symbols in the inner field represent
Place of departure
Name of driver
Name of conductor
License plate number
Date
End km reading
Start km reading
km driven
100

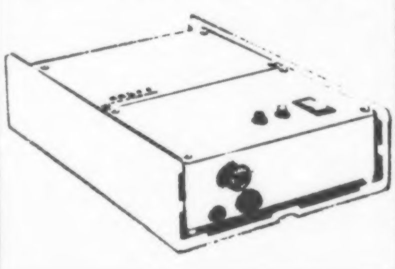
Recent developments in tachograph technology have led to the introduction of electronic drive. The advantage of this new technology is the elimination of defect-prone corrector gearboxes and cable drive systems. Electronic tachographs fall into two categories: those which utilize electronic pulse generators or impulse transmitters, regulators and drive motors, and those which use a microprocessor. The cost of a typical electronic tachograph manufactured by Engler is around $750.

## On-Board Data/Event Recorders

The recent advent of microprocessor technology has led to the introduction of on-board computers, or vehicle management systems, in the trucking industry. The devices vary by type, but usually consist of sensors attached to various parts of a truck linked to the computer, which can record information about vehicle and driver behaviour.

*Exhibit 25*

**An Electronic Data Recorder**



Typical vehicle parameters monitored by the systems include RPM, MPH, total trip miles, ignition on/off, coolant temperature and oil pressure. Information is fed continuously from the sensors to the computer. Some systems have a provision for manually entering additional information such as fuel purchases or other expenses.

At the end of each trip, or at other intervals, depending upon the memory capacity of the system, the recorded data in the computer are transferred to a cassette at the terminal for subsequent analysis. The analysis is normally performed on a desk-top computer to provide sum-mary reports indicating, for example, the number of hours a tractor was violating the speed limit, total idling time, rpm-speed ratios, start/stop times, warm up/cool down times and questionable trip or time lapses.

A wide range of on-board computer systems is currently available, varying in levels of sophistication and cost. The Tripmaster System, manufactured by Rockwell International, costs $725 for the computer and between $70 and $170 for the vehicle sensors. Off-board equipment for this system consist of a data transfer unit at $3650 and software at $950, but can be utilized for more than one vehicle.

Advanced Recording Instrument of Washington manufacture the Fleet Data Master System. The on-board equipment retails for $1200 and the off-board equipment and software is $4,365. Other suppliers of the equipment include Engler, whose on-board equipment costs between $1200 and $1700, Fleet Tech, TRW, and Cadec. The latter firm has recently entered the market with two systems, one of which utilizes a 2-way radio to transmit data automatically. TRW offers an electrical tachograph system with up to eight additional optional parameters. Several manufacturers offer similar electronic data loggers that are targeted for engineering-type test data as compared to daily operational data.

## OFF-BOARD OFF-LINE MONITORING

The concept of using the very high speed data collection and evaluation capabilities of computers to measure internal engine operating conditions in the free acceleration mode is not new and has been under active development for more than 10 years in the engine industry. The most sophisticated diagnostic systems are of the off-board type.

### Detroit Diesel Electronic Controls (DDEC)

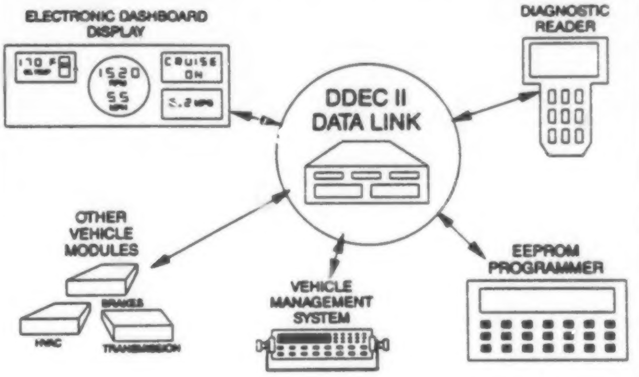
General Motors' Detroit Diesel Electronic Control (DDEC) has an internal diagnostic capability for engine functions -- a hand-held internal diagnostic reader is plugged into the electronic control module to read stored faults. The integral microprocessor-based, electronic engine control module became available in September 1985 and was designed to reduce emissions, to increase fuel economy and improve driveability and engine protection (26,27). Its major components include:

- Electronic Control Module (ECM) contains programmable read-only memory chips that provide instructions for basic engine control functions such as rated speed and power, engine governing, cold start logic and diagnostics. It continuously monitors and analyzes the system during engine operation with electronic sensors.
- Electronic Distributor Unit (EDU) regulates the electric current pulses going to the fuel injector solenoids. It also provides electronic signals to the ECM which detects and modifies solenoid valve closure for precise injection timing.
- Electronic Unit Injectors (EUI) operate on a similar principle to the mechanical unit injector system. However, a solenoid operated control valve performs the injection timing and metering functions which makes injector timing simpler and more precise.
- Electronic Sensors provide data for several functions including: signalling the ECM when a cylinder piston is at the proper firing position; monitoring oil temperature; issuing warnings of low oil pressure, high oil temperature and insufficient coolant level; and monitoring turbocharger discharge pressure.

The ECM, in turn, uses this information to: adjust fuel metering and idle speed; calibrate injection timing to achieve maximum smoke control, performance and fuel efficiency; and as an option, automatically shut down the engine during abnormal operating conditions.

DDEC offers a self-diagnostic system which monitors all engine sensors and electronic components and recognizes system faults. Diagnostic codes are logged into the ECM memory and can be read by a mechanic using an inexpensive diagnostic reader to identify the problem. An optional engine protection system monitors three critical factors (oil pressure and temperature and coolant level) and, if any one factor is outside a programmed limit, brings the engine to a controlled stop to prevent damage.

*Exhibit 26*



*Detroit Diesel DDEC Diagnostic System*

DDEC tends to reduce the maintenance and repair costs of a transit vehicle by eliminating engine tune-ups, governor adjustments, transient smoke control adjustments, and injector rack settings. It is integral to the engine and covered under the normal.engine warranty provisions. There is also a transmission-engine communications link through ATEC.

## Allison Transmission Electronic Control (ATEC)

General Motors' Allison Transmission ATEC (Transmission Electronic Control) has similar capabilities for automatic transmission functions (28). It consists of:

- Electronic Control Unit (ECU) which performs the control function for the transmission: the shift schedule logic.
- Electronic Sensors, including electronic throttle sensor, electronic speed sensor, electronic push button shift selector, electro-hydraulic valve body and a 'check transmission' driver warning light.

The electronic speed sensor replaces the governor on hydraulic automatics and measures transmission output speed for use by the ECU in calculating shift points and other control functions. Shifting is more accurate and responsive and the more precise shift point control allows more flexibility for implementing fuel-optimized shift curves and more efficient use of the engine's torque curve.

The ATEC service diagnostic feature provides early problem detection, system diagnosis and more simplified troubleshooting. As part of the service diagnostic system, thirty-one transmission and component functions such as oil temperature, oil level/pressure and clutch pressures are under surveillance. Easily obtainable diagnostic codes specify malfunction areas and simplified troubleshooting procedures walk technicians step-by-stp to the problem component. These diagnostic codes are stored in the system memory for later recall, allowing intermittent problems to be detected.

As a result of eliminating mechanical components, ATEC not only reduces the cost of maintenance, but reduces vehicle downtime and can favourably improve transmission life.

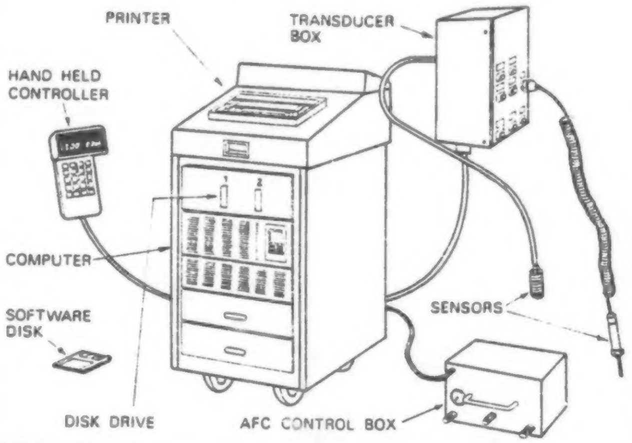
### Cummins Computerized Diagnostic System (Compuchek)

Cummins Engine's CompuChek is an off-board electronic engine test system for some Cummins engine models. But there are less than 1,000 Cummins engines in transit service in North America. This computerized performance evaluation is based on the concept of using free acceleration from low idle to high idle in combination with engine cranking to produce information that will provide a good indication of engine operating conditions. The system is not meant to replace the use of dynamometers since dynamometer testing is necessary to confirm precise engine output, specific fuel consumption, exhaust emission characteristics, etc.

Cummins's objective is to produce information that will sufficiently pinpoint problems so as to minimize the possibilities of wrong or unnecessary repairs on their own diesel engines, as well as giving assurance when engines are in good operating condition.

Exhibit 27

*Cummins CompuChek Diagnostic System*



The system will give a detailed report on the health of an engine in about one hour. The Compuchek computer, built around a Texas Instruments minicomputer, is programmed by Cummins engineers to complete a series of tests on the engine's air, fuel, cooling and lubrication systems. The system consists of a roll-around console containing the computer and a printer; a hand-held keyboard; a tape drive; and 13 timing, temperature and pressure sensors. Fittings are permanently attached to the engine to accommodate the sensors.

The electronic sensors include a special magnetic dual probe type ring-gear sensor to measure instantaneous engine speed; a cycle event marker to sense movement in one of the intake rocker levers; nine pressure transducers and two temperature sensors.

Compuchek prints fault codes that correspond to detailed explanations in an accompanying repair manual. It is programmed to run 15 different tests as shown in Exhibit 28. The system has been under test in England since 1985 by the National Bus Company, Leyland Bus and the Department of Transport with quite favourable results (29,30).

### *Diagnostic Capabilities of Cummins CompuChek*

*Exhibit 28*

| Component/Test | Measures | Procedure | Problems |
|---|---|---|---|
| **Fuel System** | | | |
| Air in Fuel | Checks for air entering the fuel system by measuring the rate of rise in rail pressure, relates to throttle response | Acquires samples of rail pressure as the technician snaps throttle open | Air leak in the fuel system high fuel filter restriction, cut injector O-rings or failed injector |
| Fuel Pump Calibration | Measures the fuel pump calibration, including throttle leakage | Measures fuel pump delivery pressure at checkpoint speeds and finds governor cutoff point | A fuel pump out of calibration, a weak governor spring, a low governor setting or incorrect injector calibration |
| No Air Rail Pressure | Measures the performance of the fuel pump with no air pressure on AFC which simulates no turbocharge boost | Analyzes samples of rail pressure at an engine speed specified by fuel pump code | A possible sticking AFC check ball, a sticking or broken AFC plunger or a wrong no-air-rail pressure setting |
| AFC Response Test | Measures the performance of the Air Fuel Control (AFC) section of the fuel pump | Measures the responsiveness of the fuel system to changes in intake manifold pressure | Sticking or broken AFC components |
| Throttle Leakage | Measures fuel pump throttle leakage as a function of engine deceleration rates | Measures the rate of deceleration with fuel and without fuel | Throttle leakage out of adjustment or throttle lingage that is hanging up |
| **Cylinder Performance** | | | |
| Power Balance | Tests the power contribution of each cylinder to the crankshaft | Collects data from acceleration snaps to give ratio of work performed by each cylinder to average of all cylinders | Faulty injector in one or more cylinders |
| Compression Balance | Measures energy removed from crankshaft as each cylinder passes through its compression stroke | Acquires samples of engine speed as the technician cranks engine with fuel solenoid off | Worn or broken valves, pistons, rings and liners; faulty injector check valves and/or bad solenoid shutoff valve |
| Acceleration Torque | Measures acceleration ability of engine with no air supplied to AFC as indirect measure of injector calibration | Calculates average acceleration and deceleration rate from the acceleration snaps of the power balance test | Incorrect injectors, wrong no-air rail pressure setting or bad injector check ball seats |
| Blowby Testing | Checks blowby pressure | Based on eight samples of blowby pressure over a one-second interval | Broken pistons/ rings; scored pistons, rings, liners; incorrectly installed pistons or liners; normal wear, failed turbocharger seal |
| **Air System** | | | |
| Turbo Response | Measures the turbocharger response to a change in the engine operating conditions | Analyzes intake manifold pressure and engine speed to determine rate at which turbocharger provides a gain after engine speed reached high idle | Wrong or rubbing turbo parts or leaking manifolds |
| Air Filter Restriction | Analyzes air filter restriction as engine tested with no load and corrected for full load | Measures the pressure drop through air filter element and inlet ducting during turbo response test | Plugged or damaged air filters |
| **Lube System** | | | |
| Three Lube Oil System | Analyzes oil pressure, oil filter conditions, regulator break, system capacity/wear | Takes samples of engine oil pressure in the main rifle at rated speed and idle | Leaks in the oil system, incorrect oil viscosity, fuel in the oil, too high oil levels |
| **Cooling System** | | | |
| Cooling Performance | Measures water pump performance and deficiencies in the radiator, pressure cap and thermostat | Measures water pump performance | Problems with water pump, radiator, pressure cap or thermostat |

## Automatic Bus Diagnostic System (ABDS)

United Technology's Hamilton Test Systems is the clear leader in North America in off-board devices with their Automatic Bus Diagnostic System (ABDS). It represents the state-of-the-art in bus diagnostic systems.

The Automatic Bus Diagnostic System (ABDS) is a computerized tool for fault identification and isolation in diesel-powered buses and their subsystems. It consists of:

- Fuel Island Unit which performs a daily checkout and consists of a computer connected to the coolant, oil and fuel dispensers and a single electric diagnostic connector to the rear of the bus.
- Maintenance Area Unit which performs comprehensive diagnostic testing and consists of a computer console, control panel and the cabling, hoses and disconnect used to interface with the bus. It is primarily used for 3,000 and 6,000 mile inspections.
- On-Board Sensors which consists of twelve voltmeters, three temperature sensors, two engine speed pickups, five current shunts and a viscosity meter (as well as bus odometer). Seventeen pressure transducers, a cylinder identification probe and an emissions probe are temporarily connected to the bus for the comprehensive tests.

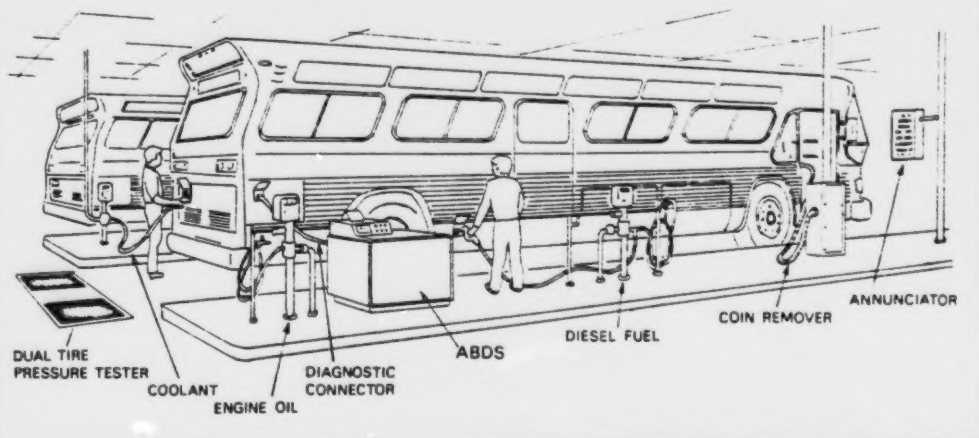
All electrical connections except the top dead center signal used in the maintenance area are provided through a cable and connector to an electronic box which is located under a passenger seat aft of the rear right wheel housing. The box is removable by disconnecting three connectors and five installation screws. The electronic box contains the components and circuitry to perform various on-board functions: bus identification number; mileage accumulator; operating condition latches; interfaces to test voltages, currents, temperatures, engine oil viscosity; and to control cranking, start inhibit and warning buzzer.

The bus-mounted sensors are connected to the electronic box with an electrical umbilical connector. The seventeen sensors that are temporarily connected to the bus in the maintenance area are bundled together and a special multiport disconnect is provided. In an effort to reduce the number of changes to the engine, the transducers are installed in the maintenance unit rather than on each bus.

Overall health of bus is checked daily during refueling operation as illustrated in Exhibit 29. A computer-based console interfaces with on-board sensors and microprocessor to automatically test the bus during a three-minute test including probe attach and release. The fuel island system is connected to the coolant, oil and fuel dispensers for automatic reading of quantities dispensed. Connection to the bus is by a single electric diagnostic connector mounted to the rear of the right-hand rear wheels of the bus. This connection is made by the operator shown adding fuel immediately after the bus comes to a stop at the fuel island.

*Exhibit 29*

***ABDS Hookup at Servicing Island***



With the capability to automatically record bus number, mileage and consumables, the system operates almost automatically and the operator has then only to disconnect the diagnostic connector when the test is completed. A bus mounted buzzer is sounded prior to crank to warn any personnel in this area and to prevent the bus from being driven away with the diagnostic cable attached, the start circuit is inhibited at all times when the cable is attached.

*Exhibit 30*

***ABDS Tests During Daily Servicing***

| | |
|---|---|
| BATTERY<br>STARTER<br>CRANKING RPM<br>EMISSIONS HC<br>ENGINE OIL VISCOSITY | AUTOMATIC ENGINE CRANK/START SEQUENCE |
| HIGH COOLANT TEMPERATURE<br>HIGH CONVERTER OIL TEMPERATURE<br>HIGH BUS TEMPERATURE (A/C ON) | CHECK LATCHES DURING PREVIOUS DAYS RUNNING |
| BUS NUMBER<br>BUS MILEAGE<br>FUEL ADDED<br>COOLANT ADDED<br>TIME/DATE OF TEST | ENTERED AUTOMATICALLY |

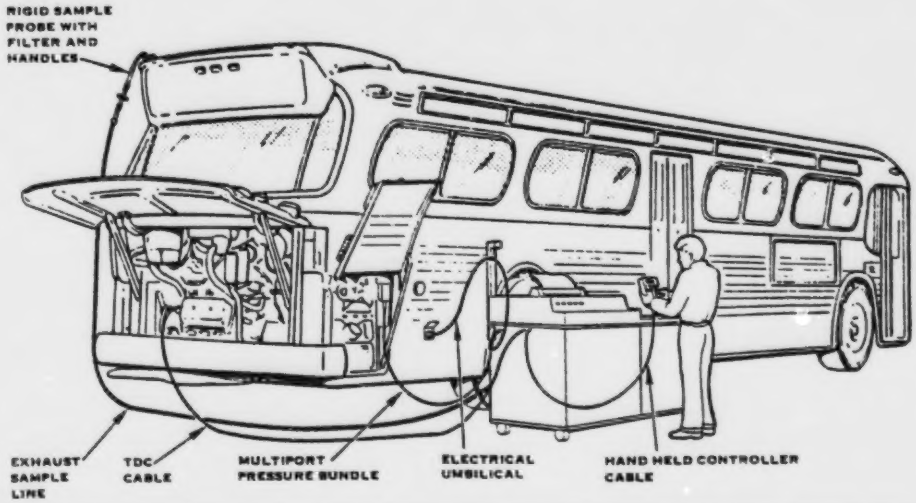
Nine tests are performed (listed in Exhibit 30) and the bus number, mileage and consumables used is recorded. Defects printed out at time of test and defective equipment can be deadlined or set out for overnight running repair. The defects are printed out at the fueling bay after the test.

During the automated testing, the system cranks the engine and records the starter voltage, battery load voltage, crank speed and ground strap voltage. Under normal situations, the entire procedure should be accomplished in approximately 180 seconds, including 80 seconds for fueling, 35 seconds for exhaust sampling, and 40 seconds for interrogation and data processing. At the completion of the daily health checks, a pass/fail test report is printed allowing the operator to either send the bus out on its assigned route or to the maintenance area for appropriate corrections.

During scheduled periodic maintenance, the bus is subjected to a thorough mechanical examination by ABDS to diagnose the cause of deficiencies identified at daily check. An illustration of the diagnostic system in the maintenance bay is provided in Exhibit 31.

Exhibit 31

***ABDS Maintenance/Inspection Application***


RIGID SAMPLE PROBE WITH FILTER AND HANDLES
EXHAUST SAMPLE LINE
TDC CABLE
MULTIPORT PRESSURE BUNDLE
ELECTRICAL UMBILICAL
HAND HELD CONTROLLER CABLE

The number of different tests is 144 and time to test, including hook-up and report printing, is 20 minutes. The system tests that are undertaken are illustrated in the exhibit opposite. A complete diagnostic checkout will take about 20 minutes -- the technician is provided printed instructions on the hand-held console. A comprehensive engine test report is produced with the test values.

Exhibit 32

***Tests During Complete Diagnostics***

- STATIC
  - ENGINE OIL LEVEL
  - COOLANT LEVEL
  - ACCESSORY DRIVE BELT CONDITION
  - FUEL & AIR LINE CONDITION
  - THROTTLE LINKAGE TRAVEL
  - CYLINDER IDENTIFICATION
  - BATTERY CONDITION
  - MANUAL AIR SHUTDOWN FUNCTION
  - TRANSMISSION FLUID LEVEL
  - BATTERY VOLTAGE
- CRANKING
  - CRANKING SPEED
  - BATTERY CURRENT
  - BATTERY VOLTAGE
  - BATTER/STARTER VOLTAGE DROP
  - BATTERY CABLE VOLTAGE DROP
  - STARTER SOLENOID VOLTAGE
  - GROUND STRAP VOLTAGE DROP
  - BATTERY JUNCTION BLOCK VOLTAGE DROP
  - COMPRESSION-RELATIVE CYLINDERS
  - FUEL PRESSURE
- RUNNING
  - WATER PUMP PRESSURE
  - WATER PUMP PRESSURE RISE
  - THERMOSTAT SETTING
  - COOLING SYSTEM PRESSURIZATION
  - HORSEPOWER
  - AIR IN FUEL
  - RADIATOR EFFICIENCY
  - HIGH IDLE SPEED
  - HIGH IDLE FUEL PRESSURE
  - DECELERATION RATE
  - BLOW BY
  - INLET AIR RESTRICTION
  - AIR TANK CHARGE TIME
  - COMPRESSOR CUT-OUT PRESSURE
  - COMPRESSOR CUT-IN PRESSURE
- RUNNING
  - LOW IDLE SPEED
  - IDLE FUEL PRESSURE
  - TEMPERATURE GAUGE ACCURACY
  - OIL PRESSURE GAUGE ACCURACY
  - POWER CONTRIBUTION--RELATIVE
  - OIL REGULATOR--CUT-IN PRESSURE
  - OIL REGULATOR--CUT-IN SPEED
  - OIL TEMPERATURE
  - IDLE OIL PRESSURE
  - HIGH IDLE OIL PRESSURE
  - INTAKE AIR TEMPERATURE
  - GENERATOR OUTPUT VOLTAGE
  - BATTERY VOLTAGE
  - GENERATOR OUTPUT CURRENT
  - GENERATOR FIELD VOLTAGE
  - GENERATOR OUTPUT FLUCTUATION
  - MAIN CONVERTER PRESSURE
  - CONVERTER IN PRESSURE
  - CONVERTER OUT PRESSURE
  - CONVERTER DIRECT DRIVE PRESSURE
  - CONVERTER HYDRAULIC PRESSURE
  - CONVERTER FILTER PRESSURE DROP
  - HC EXHAUST
  - CONDENSER FAN MOTOR VOLTAGE
  - HEATER BLOWER #1 VOLTAGE
  - HEATER BLOWER #2 VOLTAGE
  - CONDENSER FAN MOTOR CURRENT
  - HEATER BLOWER #1 CURRENT
  - HEATER BLOWER #2 CURRENT
  - FRONT BRAKE CHAMBER PRESSURE
  - REAR BRAKE CHAMBER PRESSURE
  - FLUID DRIVE FAN SLIPPAGE
  - SECONDARY FUEL FILTER RESTRICTION
  - CONVERTER STALL SPEED
  - GENERATOR RELAY SWITCH VOLTAGE
  - AIR CONDITIONING EVAPORATOR OPERATION
  - HIGH IDLE AIR BOX PRESSURE
  - AIR PRESSURE GAUGE ACCURACY

ABDS has been under development and test in New York City for over eight years. Ten GMC 5305 and 5309A buses were fitted with appropriate sensors for the New York tests. ABDS is being upgraded and modernized for additional testing in Syracuse and Flint. This includes:

- Tire Pressure
- Additional electronic fuel island tests
- Improved parameter measurement techniques
- Increase on-board data collection/condition monitoring
- Current electronic technology
- Electronic signatures for additional make/model buses
- Integration into maintenance/management information systems

ABDS is scheduled for commercial availability in 1988 but the cost has not yet announced. Many transit operators in the United States are anxiously awaiting ABDS. Although the current configuration of ABDS is probably optimal, when installing the system, extensive laboratory tests are necessary to develop electronic signatures for each system to be evaluated: Engine, Transmission, Air conditioning, Air brakes, Cooling, Engine electrical, Body electrical, Emissions. Development of electronic signatures for each make/model of bus and engine/transmission combination should be the most costly item in the system.

Equipment installed on-board each bus is not trivial either:

- Microprocessor, 17 pressure, 4 temperature and 13 voltage sensors
- Cost of equipment installation during bus manufacture or rehabilitation will be only a small fraction of later installation cost.

Installation of the entire test system on-board would be extremely costly:

- Essentially a mini-computer and test lab on each bus
- Sophisticated data telemetry and readout system required
- Would restrict ability to upgrade/modify system capabilities

The cost effectiveness of ABDS is open to debate. ABDS may be cost effective if it remains operational over the entire bus life cycle. Benefits would include: reduced downtime, reduced mis-repair/re-repair, and reduced troubleshooting time, as well as some elements of public transit service that do not have an assigned dollar value -- i.e. passenger inconvenience due to road calls.

# 8. DIAGNOSTIC SUMMARY

Transit vehicle maintenance costs are about $24,000 per vehicle per year. As maintenance costs have grown, so has the interest in ways of reducing costs while enhancing the availability of vehicles for service and reducing vehicle breakdowns and roadcalls. Diagnostic systems for transit vehicles have therefore received attention recently. These diagnostic systems can perform various functions: use monitoring, health monitoring, failure prediction, failure detection, fault isolation, mechanic education and repair verification. Each of these diagnostic functions is capable of reducing the severity of one or more maintenance problems, such as: inefficient fault isolation, improper operations/neglect, late detection of faults, excessive rework and low productivity.

The options open to the transit industry regarding vehicle diagnostic systems for urban transit vehicles may be categorized as follows:

- Make no provision for diagnostics.
- Provide special purpose test equipment in service centres.
- Provide comprehensive off-board diagnostic systems (ABDS).
- Provide integrated on-board diagnostic modules (DDEC, ATEC).

Special purpose test equipment would include oil analyzers, chassis dynamometers, decelerometers, pressure manometers, Maxwell combination chassis dynamometer/brake tester/high-speed road-test simulator or the Harris electronic engine inspection device. Comprehensive off-board diagnostic systems include United Technologies Automatic Bus Diagnostic System (ABDS) and Cummins Engine Company's CompuChek. Integrated on-board diagnostic modules include Detroit Diesel's Electronic Control (DDEC) and Allison Transmission's Electronic Control (ATEC).

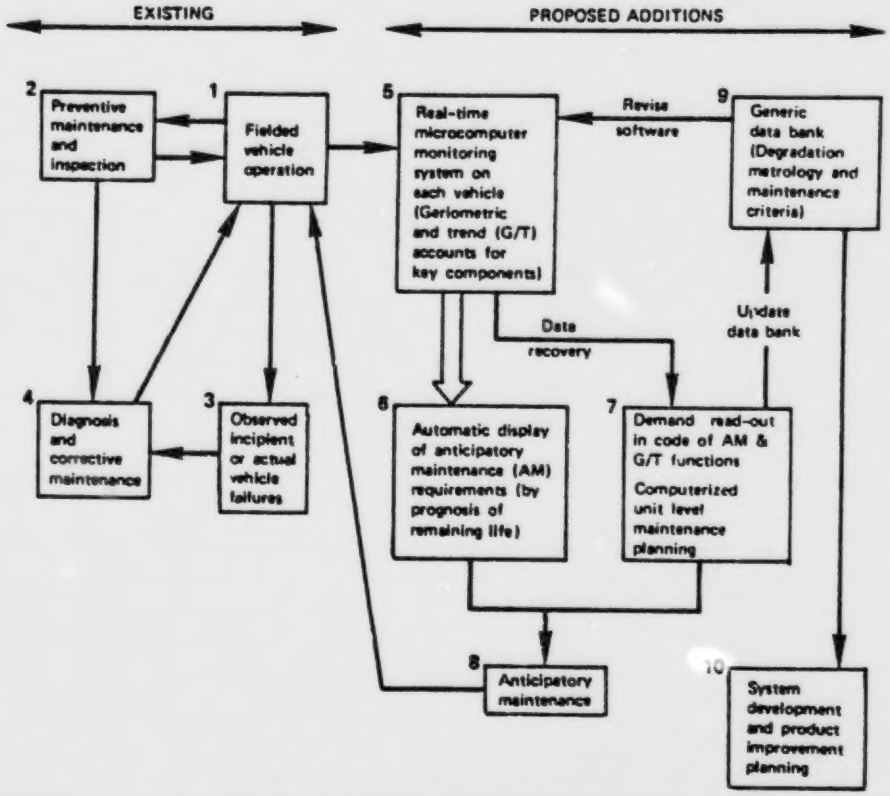
The integrated on-board modules create a simple bus diagnostic system. More importantly, linking the various components in this way lays the groundwork for more elaborate systems that will improve vehicle maintenance even further by monitoring an increasing variety of vehicle components, and eventually by tracking the actual health of a vehicle. This will be feasible since the information collected can be stored and used in the transit agency's on-going preventive maintenance activities.

## CONCEPTUAL DIAGNOSTIC SYSTEM

To illustrate the diagnostic concept, a preliminary specification for a transit maintenance management procedure is provided in Exhibit 33.

Exhibit 33

*Conceptual Comprehensive Diagnostic System*


EXISTING
PROPOSED ADDITIONS
2
Preventive maintenance and inspection
1
Fielded vehicle operation
5
Real-time microcomputer monitoring system on each vehicle (Geriometric and trend (G/T) accounts for key components)
Revise software
9
Generic data bank (Degradation metrology and maintenance criteria)
Data recovery
Update data bank
4
Diagnosis and corrective maintenance
3
Observed incipient or actual vehicle failures
6
Automatic display of anticipatory maintenance (AM) requirements (by prognosis of remaining life)
7
Demand read-out in code of AM & G/T functions
Computerized unit level maintenance planning
8
Anticipatory maintenance
10
System development and product improvement planning

Source: Reference 32.

Blocks [1] through [4] are a simplified representation of the existing system. Transit vehicles [1] are operated by the transit agency on various routes and types of services. A preventive maintenance and inspection program [2] is conducted to retard wear processes and to ascertain when the wear has reached the point requiring maintenance. In many cases, all transit operators are compelled to let degradation mechanisms proceed to the point of obvious incipient or actual failure [3] before maintenance is done because real-time techniques suitable for measuring remianing componet life have not been available. As a consequence, too much of the maintenance is corrective maintenance [5] performed after the failures have occurred. This procedure casues unnecessary secondary failures and inefficiencies in the unanticipated allocation of maintenance equipment and personnel.

Blocks [5] through [10] show possible additions to the maintenance system. On-board microprocessors can be configured as real-time monitors of key vehicle component degradation mechanisms [5]. These monitors can be programmed to track the progression of component life spans using trend analysis and geriometric accounting algorithms and to signal the pending need for maintenance just before the life span ends in failure [6]. Periodic data recovery in computer-coded form [7] can be initiated by the maintenance personnel. The combined status of all of the agency's vehicles and components would permit the optimum scheduling of maintenance in anticipation of pending failures so that the best use of fixed maintenance resources can be made in achieving maximum vehicle readiness. This anticipatory maintenance [8] can replace much of the corrective maintenance required with an attendent reduction in costs.

The periodic data recovered in computer-coded format [7] can also be transmitted to a generic data bank [9] for continuous updating of the degradation metrology and the associated maintenance criteria. As these data mature, appropriate revisions to the software of the on-board microprocessors can be made. Also, data from the data bank can be fed back to the management information system for system development and product (equipment) improvement planning process.

## DIAGNOSTIC SYSTEM PRIORITIES

It is anticipated that the point where such a conceptual diagnostics system is available is a considerable ways into the future. The building blocks are available now, however. The problem is to look at the various diagnostic functions, maintenance problems, and vehicle subsystems in order to develop a list of priorities for possible development programs.

Should a comprehensive diagnostic system be considered? Is there a particular vehicle subsystem such as the engine where there would be a large immediate payback? What particular functions of a diagnostic system are most important? What maintenance problems would it help to solve? ... These are the types of questions that will hopefully be answered in the next section of this report: Section 3 on Evaluation.

# Section 3:

# EVALUATION

# 9. EVALUATION ANALYSIS

In the previous section of this report, a review was provided of urban transit vehicle diagnostic systems. As seen, these systems offer a variety of different functions and can help to overcome various types of maintenance problems. This range of existing and promising systems must be reduced to the most suitable for specific transit applications. Their existing and potential capabilities must be fully assessed and understood.

To fully understand their capabilities, it is best to evaluate the systems based on explicit criteria, such as: commercial availability; cost (implementation, operation, maintenance); benefits (in the bus environment); time required for implementation; resources (especially transit industry support ones); operating history; reliability; ease of implementation; and technology, including issues related to hardware and software.

By determining the existing systems' capabilities in meeting these criteria, we will be able to assess the feasibility of introducing the selected applications into the bus environment at Canadian properties. Of particular importance will be an assessment of the extent to which vehicle diagnostics could reduce the overall cost of maintaining a bus -- the overall financial benefits that may result from diagnostics.

Another important concern is the particular functions, problems and subsystems that should receive first consideration. For example, which subsystems -- engine, electrical, braking, transmission, etc. -- would benefit the most from diagnostic aids? Should the diagnostic aids be oriented to on-board health monitoring or off-board fault isolation? Should a comprehensive system be considered or an incremental development program? Where will the most benefits result?

In this section of the report, a detailed evaluation of transit vehicle diagnostic systems is undertaken in order to assess the potential benefits of diagnostic aids. Two models are used in the benefit analysis: a Diagnostic Cost Savings Model (DIACSM) and a Maintenance and Diagnostics Analysis Model (MADAM).

The first model, the DIACSM model (see Appendix B), was developed by the consultants in order to assess benefits resulting from an decrease in diagnostic labour time and an increase in diagnostic/repair accuracy that would result when diagnostic aids are used.

The latter model, the MADAM model (see Appendix C), was developed by the Rand Corporation to analyze diagnostic systems for the United States Army and provides a way of assessing maintenance problem and diagnostic function priorities by vehicle subsystem. These two models are primarily oriented to the establishment of costs and benefits in monetary terms.

## DIAGNOSTIC COST SAVINGS MODEL (DIACSM)

This model was used to estimate the anticipated savings with vehicle diagnostic systems. The model, which is called a Diagnostic Cost Savings Model (DIACSM), is described in Appendix B and was developed in order to assess the following potential impacts of diagnostic systems:

- a decrease in diagnostic labour time;
- an increase in diagnostic/repair accuracy;
- an increase in the failure predictive capability; and
- overall improvement in bus reliability and/or availability.

The difference between maintenance costs in the absence of diagnostic aids and maintenance costs with the application of diagnostic aids is used as the measure of the potential leverage for diagnostic aid systems.

To apply the model, the following representative data was assembled by means of interviews with various transit maintenance managers:

- the relative percentages of maintenance time and/or labour costs spent on diagnostic functions versus repair and installation functions;
- the relative percentages of maintenance time spent by purpose (corrective, preventive or safety) for the maintenance activity, and
- the relative accuracy or reliability of repairs by vehicle subsystem.

Although the model provides an estimate of the potential benefits of diagnostic systems by vehicle subsystem and reason for the maintenance activity, the analysis is based on limited data that can only be considered as representative of current maintenance practices. Additional data from a number of transit properties would help to substantiate the results.

## MAINTENANCE AND DIAGNOSTICS ANALYSIS MODEL (MADAM)

The second evaluation model was developed by the Rand Corporation for the Defense Advanced Research Projects Agency in the United States (34). This evaluation methodology is based on two assumptions: first, that current vehicle operating and maintenance practices embody a number of problems that cause maintenance costs to be higher than necessary; and second, that diagnostic systems perform functions that can reduce or eliminate these problems.

Current maintenance problems include: manufacturing faults, improper operation or neglect, maintenance-induced faults, inefficient fault isolation, faulty malfunction diagnosis, late detection of a fault, excessive rework due to improper initial repair and low productivity.

These problems are assumed to be of two basic types: those that increase the frequency of maintenance by decreasing vehicle reliability, and those that increase the cost per maintenance action by decreasing vehicle maintainability.

Frequency of maintenance is influenced by three of the problems: manufacturing faults, improper operation/neglect, and maintenance-induced faults from maintenance actions (the more often maintenance is performed, the greater the possibility that a maintenance-induced fault will result). The maintainability or the resources used in a repair action may be affected by any or all of the following maintenance problems: inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity.

The difference between maintenance costs in the absence of diagnosis and costs with all such problems eliminated is a measure of the maximum potential leverage for diagnostic systems. Of course, not all problems will be eliminated completely and the model also takes into account the magnitude of the problems and the diagnostic effectiveness.

The model designed to implement this methodology -- the Maintenance and Diagnostics Analysis Model (MADAM) -- employs a reliability/maintainability approach. Given as inputs the number of kilometers of operation, the reliability/maintainability characteristics of the vehicle subsystems, the problem magnitudes, and diagnostic effectiveness, MADAM estimates vehicle maintenance costs with and without the use of a diagnostic system.

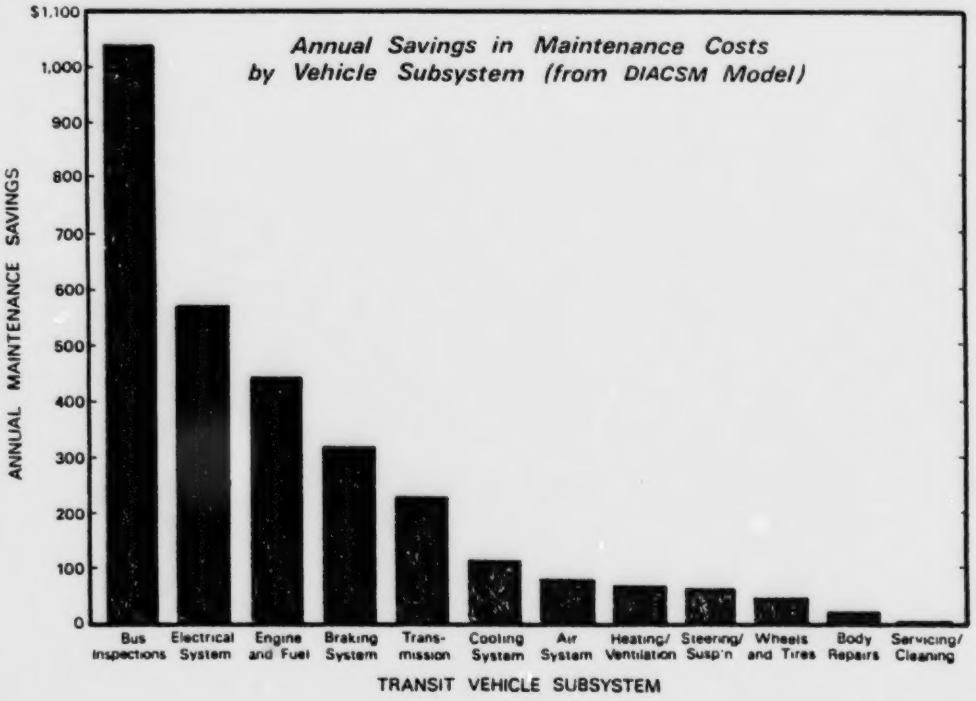
Several analyses that were undertaken (see Appendix C) illustrate the abilities of the model to identify the most important maintenance problems, examine the effects of changes in problem magnitudes or diagnostic effects, and estimate the potential savings resulting from the use of a particular diagnostic system.

## MAINTENANCE COST SAVINGS WITH DIACSM MODEL

Applying the DIACSM model (Appendix B), it was found that the total savings if diagnostics could be applied to all vehicle subsystems is $2,985; that is, if diagnostics could be applied to all vehicle subsystems, annual maintenance costs could be reduced by 12 percent or almost $3,000.

The annual savings in maintenance costs for each vehicle subsystem is illustrated in Exhibit 34. The greatest anticipated savings from the application of vehicle diagnostic systems to urban transit vehicles, apart from the benefits for inspections, are in the areas of the electrical, engine, braking, transmission and cooling subsystems. If diagnostics were applied to just these five areas, the potential savings would be $2,714 (assuming that the benefits would pass on to bus inspections). This is over 90 percent of the total anticipated savings. Very little benefits would result from incremental addition of other vehicle subsystems.

Exhibit 34

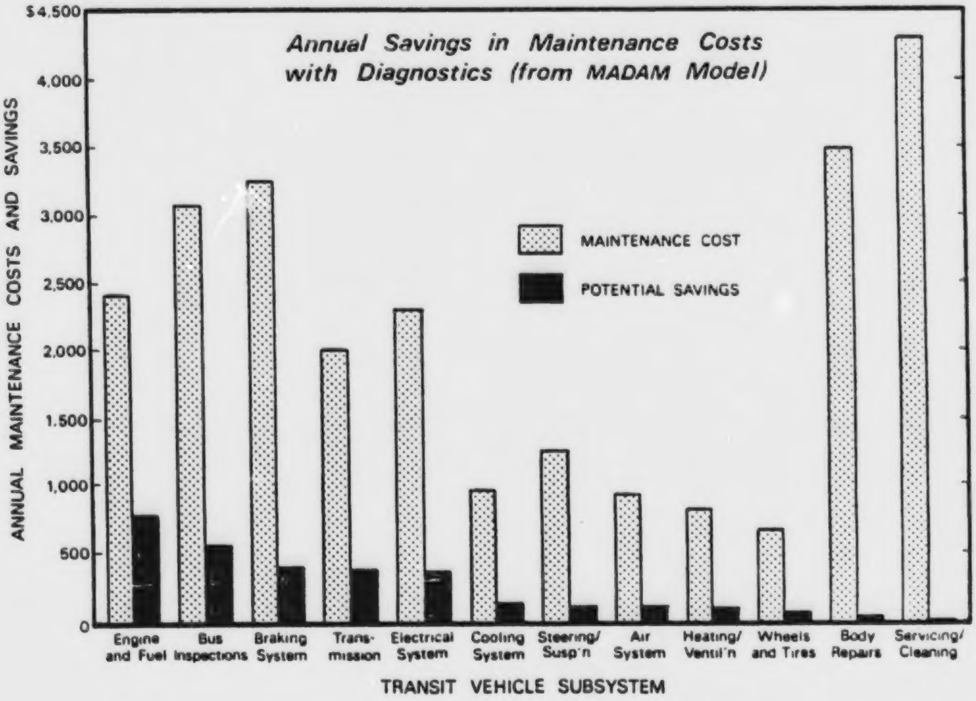


This approach sheds light on the utility of diagnostic aids by transit vehicle subsystem. It provides a means of prioritizing applications according to anticipated savings. It shows that, when considering diagnostic aids, emphasis should be placed on: (1) the electrical subsystem, (2) engines and fuel, (3) the braking subsystem, (4) transmission and (5) cooling system and that considerable benefits would also result in the inspection function.

## MAINTENANCE COST SAVINGS WITH MADAM MODEL

Applying the MADAM model, which incorporates some broad assumptions on the applicability of diagnostic aids to subsystems, the total annual maintenance costs for a typical bus with and without diagnostic aids were calculated. These results are described in Appendix C and illustrated in Exhibit 35. Using the estimated problem magnitudes and the estimated contribution of diagnostic systems in solving these problems, the potential maximum savings would be $3,088 per vehicle annually. The cost breakdown is as follows.

*Exhibit 35*



The largest probable savings would result in applying diagnostics to the engine and fuel system, the braking and transmission systems, and the electrical and cooling systems. If a comprehensive diagnostic system could be developed and applied to these systems, as well as to the vehicle testing and inspection function, an estimated annual savings of $2,604 would result for each vehicle.

If such a comprehensive diagnostic system could be developed to cover all the aforementioned vehicle subsystems, about 85 percent of the total annual potential savings could be achieved. If only the engine, transmission and inspection systems are considered, the annual savings would be about $1,700 (about 60 percent of the potential).

## QUALIFICATION OF THE ANALYSIS

Although the models used in these analyses are not perfect, the approach adopted sheds light on both the utility of diagnostic aids by function and vehicle component and the estimation of maintenance costs.

Given estimates of current maintenance costs, the operating and maintenance 'problems' that presently exist, and their magnitudes, it is possible to estimate the potential leverage of diagnostic systems. Potential leverage is the difference between current maintenance costs (which include contributions by existing problems) and maintenance costs if all problems could be eliminated.

Obviously, diagnostic systems cannot eliminate all the problems; estimates of their actual impacts are therefore necessary. These estimates are in terms of the extent to which the various problems could be ameliorated. Using fairly conservative estimates of diagnostic impacts, an estimate of the potential annual savings from diagnostic aids were calculated. These estimates provide a basis for prioritizing the implementation of diagnostic systems by function and vehicle component, as well as a means of determining the benefits to be achieved for input into a cost-effectiveness evaluation of candidate diagnostic systems.

# 10. EVALUATION RESULTS

The required technology is available for on-board vehicular diagnostic systems on surface transit systems. These systems have immediate economic benefits in terms of reduced incidence of downtime, reduced maintenance cost, and improved fuel economy. Operators of public transportation systems have recognized these benefits and are now making use of automatic vehicle monitoring systems and off-board diagnostic systems to improve their service.

The vehicle monitoring systems consist of vehicle location and status monitoring plus digital and voice communications systems and central monitoring and control systems. These systems are being implemented fairly rapidly in North America but the health monitoring aspects are secondary to the operational and driver security concerns. They are also very expensive and, in Europe, transit properties are having second thoughts as to their value.

Off-board diagnostic systems include oil analyzers, electronic fuel injection diagnostic systems, and diesel engine diagnostic systems. United Technologies Automatic Bus Diagnostic System (ABDS) and General Motors Detroit Diesel Electronic Control (DDEC) and Allison Transmission Electronic Control (ATEC) represent the state-of-the-art in off-board diagnostic systems for transit buses.

The proliferation of microcomputer-based engine and transmission control systems and the associated additional (other than diagnostic) benefits such as improved fuel economy and drivetrain control make them very serious candidates for any diagnostic system. In this chapter, a summary of the evaluation of the various diagnostic systems is provided.

## EVALUATION CRITERIA

Although the emphasis in the previous chapter and in the appendices is placed on monetary considerations, other evaluation criteria are also of importance. The estimated diagnostic system costs allow us to calculate total lifecycle costs and the anticipated annual savings resulting from the application of diagnostic systems allow us to calculate benefit-cost ratios. But availability, applicability and reliability are a few other concerns.

Basic criteria that were used in this evaluation of vehicle diagnostic systems are related to the overall goal of achieving better, more cost-effective, maintenance in the transit industry and are as follows:

- **Commercial Availability** - a measure of the current status of the proposed diagnostic system. Is the system in the design stage, undergoing research and development or a commercial product?
- **System Applicability** - a measure of the applicability to the predominant form of urban transit bus in Canada (one with a Detroit Diesel engine and Allison transmission). A diagnostic system could not be considered applicable if there is any chance that required modifications would void the warranty on the drivetrain.
- **System Reliability** - a measure of the vehicle or component ability to perform to a design standard given necessary maintenance. The degree of reliability is proportionate to the component's performance compared to the design standard and is measured based on current tests and operational experience.
- **Total Lifecycle Cost** - total life-cycle cost of developing, purchasing, operating and maintaining a particular diagnostic system for a small transit property in Canada.
- **Benefit-Cost Ratio** - total lifecycle cost of the proposed diagnostic system compared to the total lifecycle benefits (reduction in overall maintenance costs) and the anticipated period to receive a return on an investment in diagnostic systems.

## THE OPTIONS CONSIDERED

The options open to the transit industry regarding the inspection and diagnosis of faults with such systems may be categorized as follows:

- Make no provisions for diagnostics.
- Provide special purpose test equipment in service centres.
- Provide comprehensive off-board diagnostic systems (ABDS).
- Provide integrated on-board diagnostic modules (DDEC, ATEC)

These options are discussed below and a summary of the evaluation of the latter options are provided in Exhibit 36.

### No Provisions for Diagnostics

This option, in which there is no provision at all for any type of diagnostic equipment, is only mentioned to provide a complete range of options. It is not really considered to be a feasible option since just about every transit property has some form of diagnostic equipment.

### Special Purpose Test Equipment

Special purpose test equipment would include oil analyzers, chassis dynamometers, decelerometers, pressure manometers, Maxwell combination chassis dynamometer/brake tester/high-speed road-test simulator or the Harris electronic engine inspection device. This option is considered the 'base case' from which the existing annual maintenance cost estimates were developed. In this option, the total annual maintenance costs for a transit bus were estimated to be about $25,000.

### Comprehensive Off-Board Diagnostics

Comprehensive off-board diagnostic systems include United Technologies Automatic Bus Diagnostic System (ABDS) and Cummins Engine Company's CompuChek -- both designed as total comprehensive diagnostic systems.

Although the application of this option would result in an estimated annual savings in maintenance costs of $3,000, the annual cost of the system is also estimated to be about $3,000 -- mainly due to the large development and implementation costs. The net benefit to the transit operator in Canada is minimal. This option also has additional disadvantages of being relatively untested in the case of the ABDS and not really being applicable in the case of the CompuChek system.

### Integrated On-Board Diagnostics

Integrated on-board diagnostic modules include Detroit Diesel's Electronic Engine Control (DDEC) and Allison Transmission's Electronic Control (ATEC). The integrated on-board modules create a simple bus diagnostic system. More importantly, linking the various components in this way lays the groundwork for more elaborate systems that will improve vehicle maintenance even further by monitoring an increasing variety of vehicle components, and eventually by tracking the actual health of a vehicle.

This option appears to have the best benefit-cost ratio and the shortest payback period. It also has the additional benefits of being commercially available, very reliable and well-proven and an integral part of the equipment that it is intended to monitor. The major disadvantage is that there is a requirement for additional software development to analyze the information collected so that it can be stored and used in the transit agency's on-going preventive maintenance activities.

Exhibit 36

## Benefit-Cost Analysis of Alternative Diagnostic Concepts

| | Comprehensive Systems | | Incremental Development | | |
|---|---|---|---|---|---|
| | ADBS | CUMMINS | DDEC | (Plus) ATEC | (Plus) Brakes |
| Commercial Availability | Currently under test in Flint and Syracuse | Available for trucks but only for Cummins | Available for buses Detroit Diesel engines | Available for buses Allison transmissions | Not available commercial |
| System Applicability | Requires additional sensors and development of electronic signatures | Since only for Cummins engines, it is not applicable to transit buses | All new transit buses can be purchased with this option (DDEC II) | All new transit buses can be purchased with this option (ATEC I) | Applicable |
| System Reliability | Currently being tested and results are uncertain | Very reliable in the trucking industry but untested in transit | Very reliable and well proven in transit applications | Reliable and well-proven | Untested in transit |
| Development Cost | $500,000 | $1,000,000 | $500,000 | $150,000 | $500,000 |
| Implementation Cost | $250,000 plus $ 7,500 per bus | $250,000 plus $ 7,500 per bus | $ 50,000 plus $ 2,000 per bus | $20,000 plus $ 1,000 per bus | $100,000 plus $ 2,000 per bus |
| Annual Operating Cost | $ 1,500 per bus | $ 1,500 per bus | Electronic control will provide a net benefit in operating cost | Electronic control will provide a net benefit in operating cost | Automatic slack adjusters should provide net benefit in operation |
| Total Lifecycle Cost* | $3,000,000 | $3,500,000 | $ 750,000 | $1,020,000 | $1,820,00 |
| Annual Cost Per Vehicle | $ 3,000 | $ 3,500 | $ ,750 | $ 1,020 | $ 1,820 |
| Annual Benefit/Vehicle | $ 3,000 | $ 3,000 | $ 1,324 | $ 1,708 | $ 2,098 |
| Benefit/Cost Ratio | 1.00 | 0.86 | 1.77 | 1.67 | 1.15 |
| Esti. Payback Period | None | None | 1.9 Years | 2.7 Years | 3.7 Years |

* Lifecycle cost assumes a 10 year life and a 100-bus fleet and includes development cost.

## COST-BENEFIT CONSIDERATIONS

### Comprehensive Off-Board Diagnostics

The cost of developing a comprehensive diagnostic system similar to United Technologies Automatic Bus Diagnostic System for a fleet of 100 vehicle is estimated as follows:

- Basic costs of on-vehicle microcomputers are estimated to be around $7,500 per vehicle, assuming a moderate scale procurement. Total costs would therefore be $750,000.
- Data transfer and computing equipment will add $250,000 per fleet.
- Initial development costs are conservatively estimated at $500,000.
- Doubling the costs to accommodate lifetime maintenance and spares brings the total lifecycle costs to $3,000,000 for the fleet.

Thus, the lifetime cost per vehicle in the fleet is $30,000 or about $3,000 per year. If we compare this cost with the estimated annual savings in maintenance costs of $3,000 per vehicle, we can see that there would be very little return on investment from this approach.

### Integrated On-Board Diagnostics

If, however, an incremental approach is taken where maximum advantage is made of existing technologies, such as DDEC and ATEC, where additional benefits from electronic controls are achieved in fuel savings and so forth, the benefit/cost ratio appears to be more advantageous.

Since systems like DDEC and ATEC can be an integral part of any new vehicle acquisition program, the implementation cost is considerably less and only a small additional investment is required for computer equipment to analyze the information collected. Some development costs are still required, however, to ensure that the software developed will meet the needs of transit operators and to ensure that all components meet the ATA/SAE communications protocol standard.

In this case, the total lifecycle cost per vehicle is estimated at $1,020 per year with an annual benefit of about $1,700 -- resulting in a payback period of only 2.7 years for the system acquisition and development costs.

If this approach is taken as the most cost-effective option, it will be seen that the largest benefit is achieved with the implementation of the engine diagnostics. As other systems, such as the transmission and brakes, are added on, the incremental benefits are still larger than the incremental costs but not to quite the same extent. Eventually, a point will be reached where it will be difficult to justify additional features.

## POTENTIAL BENEFITS

In response to questions on the perceived value and/or areas of benefit that automated diagnostic systems could have, the following comments were received from the maintenance managers:

- the principal consensus was that the value of any system was probably in reducing the labour time involved in routine parameter checks as opposed to reducing repair times.
- there was also an expectation that the systems could and would be used for quality control of repair work; thus, reducing the number of re-repair work orders.
- in the periodic inspection area, the automatic diagnosis (parameter checks) of fluid levels and brake condition were viewed as the two most important and useful functions.
- comments were made concerning the amount of time required for the connection of the diagnostic equipment and that any system should attempt to reduce the sensor/equipment connection times.

It is anticipated that the proposed approach -- making maximum use of the currently available diagnostic equipment integral to electronic engine and transmission controls -- would satisfy the concerns of the maintenance managers and provide additional benefits of improved fuel economy and exhaust emission control.

## SOME PRELIMINARY CONCLUSIONS

In the last 25 years, electronics technology has touched nearly every industry, changing the way things are done at home and at work around the world. From household appliances to aircraft, the profound effect of the space age has centered on the development and increased use of electronics.

And buses are no exception. Vehicles that now rely on electronics to control engines will, in the future, use electronics to control everything from the starter to the brakes. But for the transit industry electronics will play an even larger role, because as surely as electronics will revolutionize the way buses are operated, they will change the way tomorrow's buses are spec'd and maintained as well.

The development of electronics for buses has been going on for some time. Component suppliers have been designing and testing products for inclusion in future vehicles but ultimately, it will be the vehicle manufacturers who will have to bring the parts together.

Vehicle manufacturers are viewing electronics as a way to improve fuel economy and durability while meeting emission standards. In the form of engine controls, electronics are new to buses. But their predecessors, automotive electronic ignitions, have been in use for some time. But the transit industry is a radically different place to do business than the auto market. Simply stated, electronics must pay for themselves before they will be accepted on a widespread basis by the transit industry. Payback, as a design goal, is a concern of all transit managers. The time limit of the payback period is also generally agreed to be 2 years.

But the key to payback depends on who develops the electronic component. If the manufacturers and subsystem suppliers can get together then costs will be controlled. One of the main items of interest in the trucking industry is the development of an electronic signal synthesizer that will interface with all vehicle electronics and on-board computers. The development of an ATA/SAE bus has already published a proposal on data format. Transit should probably use same data format. What is pulled out of the vehicles still has to be processed and analyzed, so there will always be a very large market for proprietary software. This software will, of necessity, incorporate some expert systems aspects.

# Section 4:

# DEVELOPMENT

# 11. DEVELOPMENT TRENDS

The key event which has already precipitated a radical change in on-board diagnostic systems is the advent of the microprocessor. From a hardware viewpoint, most modern electronic equipment either is, or will soon be, microprocessor-based.

The high capital costs of electronic systems, however, compared with that of the vehicle itself, and their space and payload implications, necessitates some form of 'system integration'. The usual approach to achieve systems integration is to purchase a 'turnkey system' from a single supplier. While that supplier may only manufacture part of the system, responsibility for the provision of the remainder, and hence system integration, is also undertaken by the supplier. Large scale, high investment, multi-disciplinary projects are the norm for the turnkey approach. For low unit cost, low volume projects such as electronic systems for urban transit buses, the return on investment is likely to be insufficient for the turnkey approach.

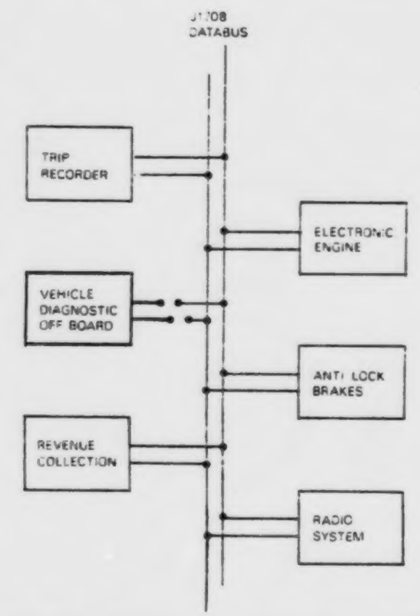
An alternative approach to systems integration exists whereby the customer specifies the functional requirements of the systems, and the detail mechanical and electrical interfaces. This approach is not uncommon in industries which have unique systems. It does, however, require a considerable investment on the part of the customer in technical expertise and capabilities.

Now that all electronic systems being evaluated or developed for use on buses incorporate microprocessor technology, it becomes possible to adopt a new approach to systems integration. By grouping together similar systems and using information transfers between them, 'rationalization' (i.e., integration -- the minimum use of hardware) and hence lower costs can be readily achieved. Specifying the information interface, instead of the traditional mechanical/electrical interface, also enables each system supplier to supply a more standard equipment.

To illustrate the concept, Exhibit 37 shows a range of on-board vehicle systems at present being used in passenger service. In essence the arrangement is a local area network with major subsystem groups (propulsion, communication, diagnostics, revenue) linked by an 'information interface'.

Exhibit 37

*Systems Integration/Rationalization*



**Propulsion Control.** Electronic and transmission engine controls using microprocessors are currently being evaluated by various transit agencies. Given that the manufacturers involved can also provide for the electronics required for engine management and the vehicle's electrical supply, these functions can be readily combined into one package. Such a package would incorporate the vehicle control logic functions, presently achieved by relays, diodes and so forth.

**Diagnostic Systems.** From a purely conceptual viewpoint, vehicle condition monitoring should be incorporated into the propulsion package, given that the engine, its supporting systems, and of course vehicle utilization are its major concern. However, the considerable scale of the installation required for sensors, cabling, etc. is likely to make a separate unit more appropriate; if only as a data concentrator.

**Revenue Collection.** A modern electronic magnetic-card based revenue collection and control system incorporates a microprocessor and a removable data storage module. It may also include a keyboard and a display unit. It is therefore an intelligent terminal, capable of being used to assist the other on-board equipment.

**Radio Communications.** Newer radios are microprocessor-based and incorporate the data telemetry function which at present may have to be provided externally. Digital communications have many uses, including automatic vehicle location for real-time monitoring and control and transference of other operational information to a central control.

## ON-BOARD VEHICLE SYSTEMS

As was seen in the previous evaluation section, providing on-board integrated diagnostics would appear to offer the most potential for transit operators. Before outlining a program of diagnostic development, however, it would be worthwhile to review some of the trends and technological strategies in the industry. To understand the direction in which changes will occur, it is helpful to look back at the kinds of changes that have occurred in the past.

Three overlapping periods are evident: the first from around 1965 to 1980 in which electronics consisted mainly of stand-alone components such as simple electronic ignition modules; the second from 1975 to 1900, which is being dominated by special purpose independent systems like electronic engine controls; and a third from 1985 to 2000 in which vehicle electronic systems are beginning to be integrated to include several vehicle functions such as traction control combined with anti-lock braking (34).

In the future, it is anticipated that on-board vehicle systems will have a number of different features and benefits. The continued deployment, however, of standalone electronic module-based systems and the attendant cadre of sensors, actuators, electrical circuits, and connectors cannot hope to provide an acceptable level of quality and reliability in the future (35). In this chapter, some of these trends in electronic systems will be discussed with respect to the vehicle components affected.

### Electronic Engine Control

There is immense potential for improvement in engine technology for buses in the near-term. Examples include self-diagnostic, maintenance-free electronic controls with engine programming capability.

Today is the dawn of the age of electronically controlled heavy-duty diesel engines. Detroit Diesel announced a production "electronically controlled fuel injection system". The Detroit Diesel Electronic Control (DDEC) engine has demonstrated fuel economy improvements of 10.15% and 10.81% in tests by Detroit Diesel Division (36). The advantages of electronically controlled engines are not limited to improved fuel economy and covers many other aspects.

One of the most desirable advantages of electronic engine control for the transit operator is the versatility of variable engine performance characteristics. While this is available to some extent with DDEC, it should be possible to replace a PROM chip to a point that each individual route could use an optimum engine rating. Optimum versatility in engine ratings will be a challenge for manufacturers. Common characteristics will have to be designed for pistons, combustion chambers, injectors, etc. to perform efficiently at 200 or 600 horsepower.

In the realm of electronic engine controls, we have two prime maintenance considerations. First, all electronic systems must self-diagnose. This includes not only electronic components of the system, but all sensors, actuators and mechanical components. Second, all sensors, actuators, linkages, mechanical devices, wiring, etc. must be durable, reliable and serviceable.

### Integrated Powertrain Control

Electronically-controlled driveline components have a potential to benefit future transit vehicles. Allison Transmissions Electronic Control (ATEC) shows that transmissions, for example, can be controlled by electronics to achieve better overall fuel economy and greater component durability and a lower operating cost is foreseen. The electronics must be fully self-diagnosing, compatible with all other on-board electronic systems, add to the vehicle's operating versatility and fail-soft rather than putting a vehicle out of service.

Transmission controls are currently being integrated with engine controls to provide total powertrain control. Work is also being undertaken to integrate this new powertrain control with anti-lock braking control. The result of this overall functional integration is traction control. Another trend in the powertrain is an increases in durability. Driveline component durability should match the vehicle life. That is frequently happening today, but tomorrow's vehicles will be more durable and driveline components will have to comply. The emphasis here will probably be on substantially improving seal performance.

### Electrical Reliability

A broad quality range exists in available lighting componentry and circuitry today. Sealed stop and tail lights have proven to be reliable and durable. Other devices are subject to corrosion in the socket area and early failure. A source of continuing difficulty is the wiring. If conventional wiring is to be used, a way must be found to make it impervious to contamination. Wiring is subject to corrosives such as road salt. Once the corrosive contaminant reaches the conductive sections of the wiring, it migrates through the entire circuit causing corrosion in all susceptible components. The limited sealed wiring systems now available prevent most of this type contamination as long as they are not altered.

One possibility for more reliable and maintainable lighting and electrical systems is the technology of multiplexing. The feasibility of computer-controlled multiplex wiring system for automotive applications has been demonstrated. This type of system would provide many benefits. For one, it would stem the proliferation of circuits. Electrical systems in commercial vehicles have been steadily becoming more complex: from the 20 or so circuits in the 1950s to the 100-plus circuits of today.

A multiplex system might also solve the difficulty of electrical current regulation. Some type of current regulation to lighting systems could eliminate high inrush currents and broken filaments that are at the root of many lighting failures. This would also allow more rugged, low-resistance construction of components. Although multiplexing may not be applicable to the battery charging circuit, current regulation is critical here. The primary source of premature battery failure is overcharging. Different transportation applications often require different battery charging configurations. A versatile charging system that is not application sensitive needs to be developed for future vehicles.

It is clear that computerized electronics will play a role in the electrical systems of future buses and these on-board electronic/computer systems will have self-diagnostic capabilities.

### Electronic Braking Systems

Today's braking systems consist of a group of components that must work well together to achieve dependable performance (and that doesn't even begin to consider durability, serviceability, maintainability, etc.). Yet we have no integrated manufacturer of brake systems. Various components are designed and manufactured by separate companies to their design specifications with little regard for standardization.

Recent testing demonstrates the lack of standardization in brake apply and release times (37). Generally speaking, brakes are needed that are more effective, more maintainable and more durable. Brake balance problems associated with poor timings, poor torque balances, uneven and unpredictable wear patterns, and safety performance issues will have to be solved. Electronic braking systems offer potential.

The government will mandate anti-lock brake systems at some point in the future when these systems have proven effective and reliable. In addition to being effective and reliable, they should be very maintainable, very durable and exhibit excellent serviceability. New electronic systems will probably be fully self-diagnosing, compatible with all other on-board electronic systems, add to the vehicle's operational versatility and fail soft rather than putting a vehicle out of service.

### Adaptive Suspension Systems

Beyond the critical issue of brakes are a few other chassis considerations for tomorrow's buses. In view of electronic controls, materials advances and the user need for maximum maintainability, suspension systems will probably be redesigned to substantially higher performance levels. Today's suspension systems do not function adequately with radial tires, which have become the de facto industry standard (36). Tomorrow's suspension systems will probably provide performance under all operating conditions.

The growing capability of electronics will allow adaptive control of the suspension which has been restricted to a passive response. In order to control ride height and dynamic response of the body, an electronic system will sense displacements and accelerations in the suspension system and will control suspension and damping independently at each wheel. There will be a continuous modulation of devices like valves to control shock absorber damping but with no external power input. Electrically-actuated front wheel steering is also being considered.

### Self-Contained Diagnostics

In many of the preceding applications such as braking, engine and transmission control, the requirements of safety dictate that the electronic control unit 'knows' what is going on in the system. Sensor signals are limit-checked before use and a safe course of action taken if the signals are found to be out of limits or inconsistent with other system inputs. It is therefore possible to arrange a small extension of this safety regime to provide data on the detected fault condition.

The electronic control unit has the further benefit of being able to correlate and check for inconsistencies of system parameters during normal running; for example, in a diesel fuel injection system, the presence of fuel pulses indicated by the injector needle lift sensor above idle speed with zero accelerator pedal demand would indicate a fault in the position sensor on the fuel metering device. This is a simple matter for the microprocessor handling these parameters to report, but rather more difficult for external equipment to have access to all this data.

The trend of greater integration of functions into electronic control units and that of increased use of microprocessors is in line with the need for improved self-diagnostics at reduced cost. This is even more evident where requirements dictate that the checking functions are already performed by the microprocessor.

### Adaptable Software

The trend in electronic controls on-board vehicles indicates a strong need for software. Models of powertrain and chassis performance will be a vital part of software development programs. Accurate and precise control systems will require the development of more sophisticated control algorithms. Software and data management techniques will be derived from the data processing industry, with adaptations to fit the unique aspects of the bus environment.

On of the major advantages will be that changes to suit the needs of particular transit operators or even particular routes can probably be accomplished with suitable software, rather than hardware, modifications, as is the case with electronic engine controls.

## SYSTEMS RATIONALIZATION/INTEGRATION

Within each vehicle subsystem group, a measure of integration is currently being developed -- in particular within the propulsion package -- and the rationalization/integration process would be completed by linking them together. This intersystem link acts as an information interface by enabling data obtained by one system to be used by another.

With this arrangement, the diagnostic system can provide information such as vehicle identity, garage identity, distance travelled, time, and so forth to the radio communication system for vehicle location purposes. The revenue collection system can act as a computer terminal for all the rationalization schemes. In addition to the normal man/machine interface that might be provided (keyboard and display), it can provide a print-out and enable data to be transferred to and from the maintenance personnel by means of a removable data cassette or EPROM module. Data regarding the bus assignment, entered by the driver into the revenue system, can also be provided to the radio communication system for vehicle location purposes.

The intersystem communication link utilizes the serial data functions associated with modern microprocessors. As such it uses the minimum of hardware. Unlike various multiplexing developments, the intersystem link is required to transmit only a limited amount of information.

In conclusion, the technology is available now for monitoring most of the required parameters on-board a transit vehicle. It is being brought in for other reasons, however, such as for electronic engine controls or anti-lock braking systems. What is required is to ensure that the various devices are able to communicate with each other, that the systems are integrated and rationalized and that excessive duplication is avoided.

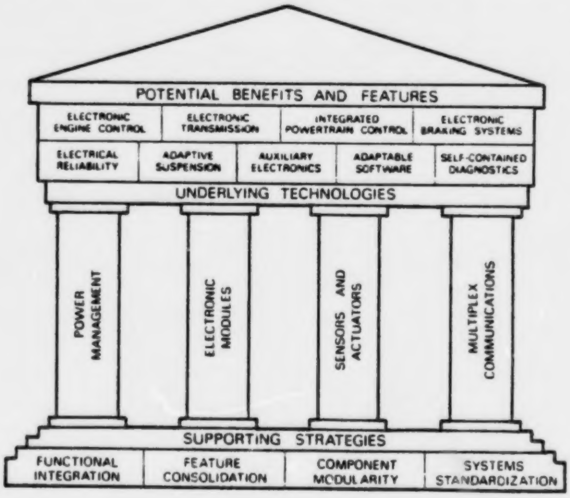
In the trucking industry, a joint committee of the American Trucking Association and the Society of Automotive Engineers have developed standardized protocols so that this will happen in the trucking industry. these standardized protocols are being accepted 100 percent by manufacturers. This industry standard will be discussed in greater detail in the subsequent chapters.

# 12. DEVELOPMENT TECHNOLOGIES

Many of the probable (or at least possible) new features of urban transit buses such as self-contained diagnostic systems, adaptable software, integrated powertrain control, and electrical reliability are based on new electronic control systems and traits. In order to make some of these features a reality, it will be necessary to develop new technologies that take full advantage of the flexibility of electronics.

*Exhibit 38*

***Probable Future Diagnostic-Related Developments***


POTENTIAL BENEFITS AND FEATURES
ELECTRONIC ENGINE CONTROL
ELECTRONIC TRANSMISSION
INTEGRATED POWERTRAIN CONTROL
ELECTRONIC BRAKING SYSTEMS
ELECTRICAL RELIABILITY
ADAPTIVE SUSPENSION
AUXILIARY ELECTRONICS
ADAPTABLE SOFTWARE
SELF-CONTAINED DIAGNOSTICS
UNDERLYING TECHNOLOGIES
POWER MANAGEMENT
ELECTRONIC MODULES
SENSORS AND ACTUATORS
MULTIPLEX COMMUNICATIONS
SUPPORTING STRATEGIES
FUNCTIONAL INTEGRATION
FEATURE CONSOLIDATION
COMPONENT MODULARITY
SYSTEMS STANDARDIZATION

To succeed in achieving the overall functional integration that will characterize these new features, electronic developments for vehicles will focus on the following key building blocks: the vehicle's electrical power supply, electronic control modules, sensors and actuators, and multiplex communications systems.

## POWER MANAGEMENT

The cornerstone of on-board vehicle electronic control systems is the electrical power supply. Electrical power supply requirements have increased continually over the years. Recently, requirements have been added to accommodate the trend to fuel injection, including electronic fuel pumps and multi-point injectors. Future trends point to requirements for heated windshields, anti-lock brake pressure control pumps, continuous front position/identification lamps, and electric power steering. Electrical load requirements may eventually include air conditioning compressors and electric quick heating features.

The reason for shifting load requirements such as cooling fans or power steering from the engine drive to the vehicle's electrical system lies in the relative ease in applying optimum control to electrically-driven, as opposed to direct-driven, accessories. Also, with the new-design fuel efficient powertrains operating at higher manifold pressure, vacuum-powered actuators are being replaced by electrically-powered equivalents. This started many years ago in passenger cars with the replacement of vacuum-powered windshield wipers with electric wipers, and now, speed control servos, automatic temperature control servos, and even the brake booster servo are all being selectively replaced by electric equivalents.

It is believed by some that this increasing requirement for electrical power will lead to a dual voltage power distribution system. The 'low' voltage supply (12 volts) will power most of the vehicle's electrical and electronic products, including the lamps. The 'high' voltage supply (at a voltage between 24 and 48 volts) will power heavy loads such as steering motors, chassis hydraulic power sources and motor-driven air conditioning compressors. The concept of using two batteries or a center-tapped battery as a key component of the dual voltage power supply has a number of cost and reliability disadvantages. From a systems point of view, however, this may be the best decision considering overall vehicle cost, weight, reliability, and fuel efficiency.

The feasibility of a dual voltage system will depend to a great extent on the development of suitable batteries. These batteries must provide high energy density, flat discharge curves, tolerance for a variety of duty cycles, and high reliability. Battery reliability will be increasingly vital as the battery will assume the role of the backup power source for critical vehicle functions such as steering.

Battery charging circuits will be electronically controlled. This will require new types of sensors to accurately measure the battery's state of charge. The system will include active load management to unload the engine on startup or at idle. Under such conditions, load shedding will be common and loads will be assigned different priorities as environmental conditions vary.

Vehicle manufacturers, electrical and electronics component suppliers, and technical professional organizations such as the Soeciety of Automotive Engineers (SAE) and the Institute of Electrical and Electronic Engineers (IEEE) are working to develop a new power supply standard for the 1990s.

## ELECTRONIC MODULES

Vehicle electronic-control modules designed over the past two decades have generally been highly specialized for their application.

In looking at many of these recently designed stand-alone vehicle electronic modules, many similarities are found. Many modules are microcomputer-based and the instruction set is usually contained by masked ROM, but EPROM is now frequently substituted, providing additional flexibility to accommodate fast turn around for development changes. The module usually contains a regulated power supply for the microprocessor and other critical circuits and some kind of conditioning, demodulation, detection or A/D conversion is used for dedicated sensor inputs. Output switches are used to drive system actuators, or a display driver is provided for instrumentation modules. Finally, the module often contains a watch-dog timer to assure reset of the microcomputer.

This indicates a trend for module hardware to become more standardized in architecture, communications and physical construction. There is also a shift from hardware to software intensive design for new applications. In fact, there is probably a potential opportunity for some very generic modules that would only require local programming of the EPROM, or other memory device, to handle a wide range of service requirements.

Total on-board processing capability of future buses will be approaching that of today's typical mainframe computer. The bus's multiplexed network will be heavily dependent on software. Models of powertrain and chassis performance spanning the extremes of vehicle operating conditions will be a vital part of software development programs. Accurate and precise control systems will require the development of more sophisticated control algorithms.

The continued development of thick film and other circuit technologies that have demonstrated reliability advantages at temperature extremes will be very important to the growth of vehicle electronics in the 1990s.

## SENSORS AND ACTUATORS

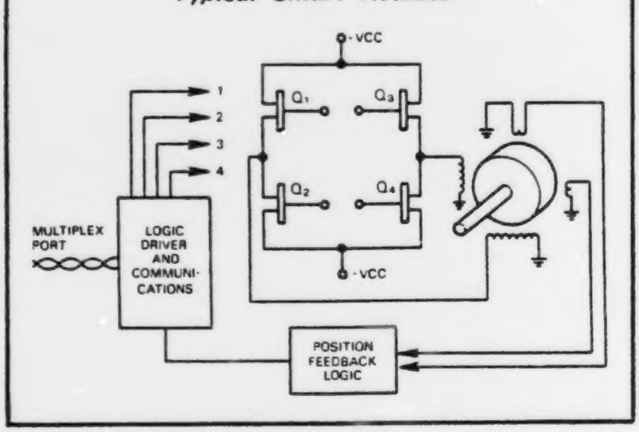
The reason for new application of electrically-driven accessories is not efficiency per se, but in the relative ease of control. The effective use of control often yields the desired efficiency.

Electronically commutated or brushless DC motors offer some promise to extend the capability to control certain actuators. The solid state switches used to conduct current to the windings of a brushless DC motor may be driven by complex switching logic in contrast to the simple fixed pattern provided by the commutator of a brush-type motor. The switching logic may be varied -- even microprocessor driven -- to provide unlimited flexibility to vary speed, direction, and power consumption.

Candidate early applications for electrically commutated motors or smart actuators include the climate control fan motors, cooling fan motors, and fuel pump motors. As smart actuators become commonly available building blocks, engineers will deploy them for the design of systems not yet envisaged. Also, diagnostic capability can be designed in the smart actuator so that it can report the status of its health to maintenance personnel. This will significantly improve service diagnostics by allowing capture and storage of large databases. Data on vehicle performance can be accumulated enabling a statistical projection of component life expectancy. This should lead to the benefit of providing for optimally programmed maintenance.

Exhibit 39

*Typical Smart Actuator*



Source: Reference 35

Analogous to smart actuators, is the anticipated greater deployment of sensors having varying levels of built-in microprocessor-based electronics. These sensors, already being used in some applications, will probably include a multiplex communication port that may be used to provide data to other modules, actuators, or sensors, and to provide diagnostic data as appropriate.

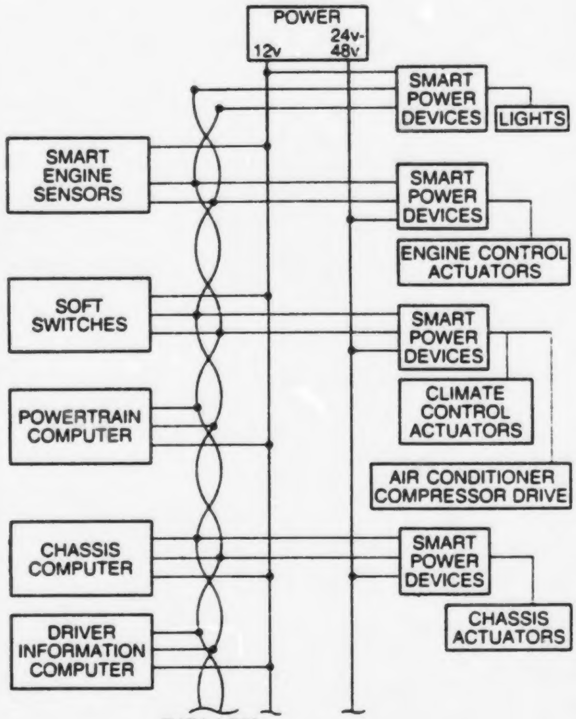
Sensors and actuators will more frequently include the capability for local data processing, diagnostics, and multiplex communication with secondary systems. Very high speed priority data from the sensor to a critical module will probably be hard-wired with dedicated transmission lines.

## MULTIPLEX COMMUNICATIONS

Standardized multiplex communications, in which two or more pieces of data can be transmitted across a single channel, is viewed as a type of distributed control architecture to tie all the components together and achieve a large number of benefits. For example, wiring bottlenecks would be reduced, as would the total number of circuits and interconnects and the total quantity/cost of wire and connectors. The reliability of the electrical system would be improved and it would facilitate information sharing between processors, increasing the feature content. It would facilitate flexibility to make late/running changes to vehicle system and it would facilitate diagnostics for assembly and service.

*Exhibit 40*

***Multiplex System and Dual Power Supply***


POWER
12v
24v-48v
SMART POWER DEVICES
LIGHTS
SMART ENGINE SENSORS
SMART POWER DEVICES
ENGINE CONTROL ACTUATORS
SOFT SWITCHES
SMART POWER DEVICES
CLIMATE CONTROL ACTUATORS
POWERTRAIN COMPUTER
AIR CONDITIONER COMPRESSOR DRIVE
CHASSIS COMPUTER
SMART POWER DEVICES
CHASSIS ACTUATORS
DRIVER INFORMATION COMPUTER
DATA LINK

Source: Reference 34

A multiplexed system architecture will be adopted to make system integration more effective. Exhibit 40 shows how components could be linked by a data-carrying signal network and a power distribution system for each of the system's two operating voltages.

The data link will create a network to share information with the vehicle's microprocessors. Each processor places signals on the network where they will be available to other components. The processors will also receive signals from other components via the network. Sensors and actuators will have smart interfaces so that they can communicate with the multiplex system. In the event of failure, firmware will provide 'limp-home' capability.

This then is the technology upon which the future will be built -- power supply, electronic modules, smart actuators and multiplexing -- but what of the strategies to make proper use of the technology.

# 13. DEVELOPMENT STRATEGIES

At SAE's 1986 Conference on Transportation Electronics, a talk was given on the future of electronics in commercial vehicles, in which 54 areas were suggested for electronic systems. The study showed that $12,000 would be added to the cost of a vehicle for 35 of the 54 systems that would be available in the '90s. Many transit operators are installing or considering automatic vehicle location systems, passenger counting systems, new revenue collection systems, radio communication systems, electronic engine and transmission controls, and health monitoring and diagnostic systems -- all based on the use of electronic systems.

With that many systems, there is a real need for their integration into a comprehensive electronic system so that their benefits can be realized without severe cost penalties. Integration is needed to eliminate redundancies (added cost), reduce overhead and complexity, and reduce inefficiency (consolidation of features). Modularity is needed to improve reliability and flexibility and standardization is needed to ensure a viable market for manufacturers.

Present design philosophy is to add an electronic box for each feature. This works well for simple systems such as a tachometer or clock, but as such features as trip recorders, passenger counters, and engine controls are added, the system becomes more complicated and cost increases. Not only do costs increase for the added devices, but also their maintenance costs rise. The increased number of electronic items leads to a redunancy of sensors, wiring and indicators, reducing efficiency.

A different design philosophy is needed to provide additional features to transit operators without redundancies and with increased flexibility.

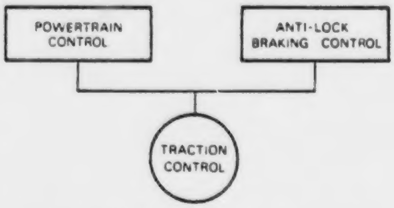
## FUNCTIONAL INTEGRATION

Electronic systems on-board transit buses typically consist of independent electronic modules, each providing separate features. In an integrated system, however, the electronic modules would no longer work independently. Functionality could be shared bewteen modules, eliminating much duplication of effort. With a properly designed integrated system, the improved efficiency can be translated into reduced complexity, increased functionality, and reduced cost.

Integration, of varying degrees, may be accomplished through the application of several techniques: signal multiplexing, consolidating additional features into existing modules, and distributing functions throughout the system. While these techniques are sometimes used independently, a fully integrated system would use a combination of the three. Exhibit 41 provides an example of functional integration.

*Exhibit 41*

***Example of Functional Integration***



**Traction control achieved with only added software and the functional integration of powertrain and anti-lock braking control**

On urban transit vehicle, there a large number of areas for integrating electronic modules. Three will be discussed here: signal multiplexing in the electrical area, feature consolidation in the information area, and distribution of functions in the real-time control area.

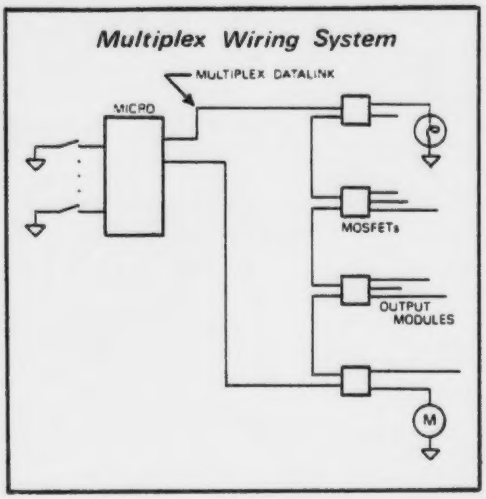
### Signal Multiplexing in the Electrical Area

In present wiring schemes, heavy gauge wire together with heavy duty switches and relays control the lights, horn, and similar components. Problems with this scheme are wiring complexity, large mechanical switches and relays, and no knowledge of a failure except when another driver alerts the operator to a failed light.

A simple lighting network is needed to integrate the above products. Only a limited amount of data such as On, Off, and diagnostic information needs to be sent across the network. There are several schemes for integrating the lights, relays, solenoids, and switches into a network.

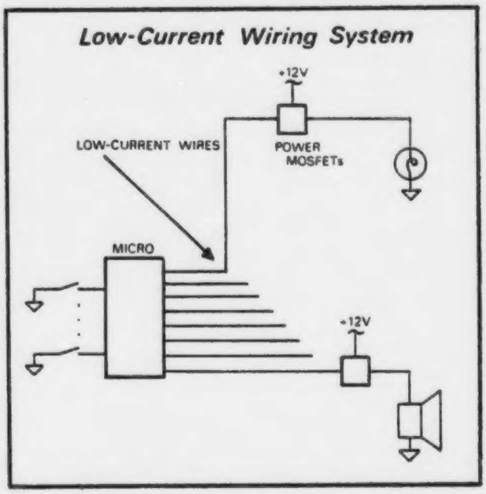
Lighting networks of the 1990s will probably evolve around power MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) with analog and digital CMOS (Combined Metal Oxide Semiconductor) elements. The MOSFETs would increase reliability and simplify manufacture. Power MOSFETs, being voltage controlled, usually need only a small gate-current pulse to switch on and off. This allows them to be switched at a high frequency, up to 25 MHz, controlling current levels up to 100 A. Larger

*Exhibit 42*



***Multiplex Wiring System***

*Exhibit 43*



***Low-Current Wiring System***

current levels can be achieved by paralleling similar units. With incorporation of digital and analog CMOS components, diagnostic and failure capability can be designed into a small package (41). MOSFETs suitable for widespread use in harsh transit environments, however, are cost prohibitive at the present time.

A total multiplex wiring system with modules containing several MOSFET ICs is shown. The network's advantage is a simplified wiring scheme. However, network failure modes could cause potential problems. If the multiplex network is shorted to ground, a module or modules might not function, which could lead to loss of control of lights, horn, etc. Redundant circuitry is needed for the critical areas. GM is marketing a vehicle using this scheme now.

In another network shown, low current switches or a microprocessor-based unit controls the power MOSFETs directly. Reduced assembly costs, layout flexibility, and improved reliability are the main benefits. Multiple wires combined in a flat ribbon with protective PVC sheathing allow for easy network construction. Jaguar and the Lucas Group use this type of network in their experimental vehicles.

The SAE Vehicle Network for Multiplexing and Data Communications Sub-Committee has identified three broad categories for multiplexing, based on application: remote-control applications, parametric data transfer applications, and real-time control applications.

Remote-control applications include the electrical networks on buses to minimize wiring complexity and allow for failure-mode indications of electrical components such as rear signal lights. However, other benefits from integration into one system with computing capability are electrical load management and features such as variable speed radiator fan motor control for more efficient engine cooling.

## Feature Consolidation in the Information Area

Just as this 'information age' decade supplies everyone with more information than can be digested, so can the transit industry's use of all the possible electronic devices available. A brief list of the more promising devices for the future includes navigation equipment for vehicle location, electronic displays, electronic trip recorders, crash recorders. digital radio communication systems, electronic engine and transmission controls, diagnostic equipment, and on-board monitoring equipment.

To avoid redundancies and inefficiency in obtaining and displaying information, an information network is needed. In the trucking industry, the SAE's J1708 datalink will become the industry standard, while J1850 covers the automotive communication network. Each will provide sensor, status, and diagnostic information to all the attached modules; each of them, in turn, can capture the unique information needed. The J1708 datalink is the one that is most applicable to the transit industry.

The J1708 document defines the serial data bus interface as a modified RS-485 transceiver. The link is bi-directional and operates at 9600 baud in a standard 8-bit, no parity, 1 stop bit, nonreturn-to-zero format. Each messages is separated by a minimum of 12 bit times with a method of collision detection and bus re-access defined in the document. The maxium message length transmitted furing vehicle operation is 21 bytes. With the J1708, the electro-magnetic interference (EMI) problems are minimal with the 9600 bps baud rate using a twisted-pair. While the system integrator need not take steps against EMI, care should be taken to route the twisted-pair away from relay-type loads (40,41).

The companion J1587 document creates a significant stride in standardizing the information on the J1708 network. It defines the format of messages and data communicated between microprocessors. Over 80 parameter identifiers have been allocated to parameters of general interest from the engine, transmission and other vehicle components. In the area of diagnostics, the J1708 datalink will have significant impact on standardized tools in the near term.

Two different integration schemes are shown using the J1708 network. A typical system for fleet opera-

Exhibit 44

**On-Board Network Integration**

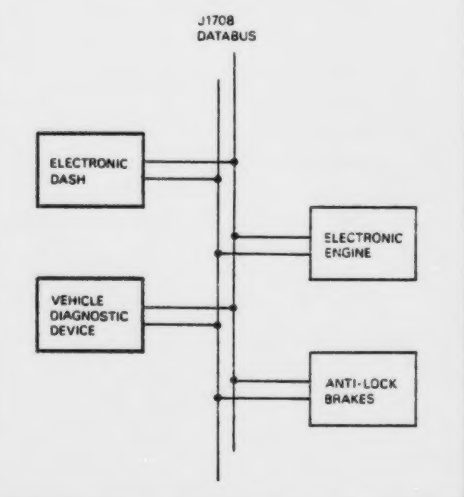
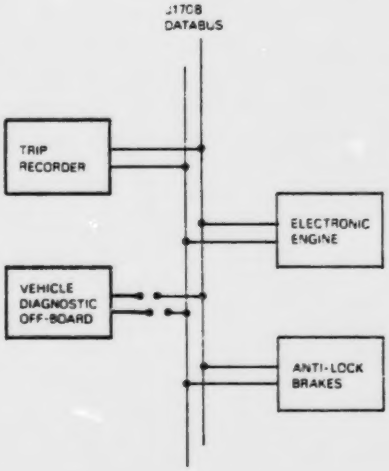


*Exhibit 45*

***Off-Board Network Integration***



tion would have a trip recorder for driver monitoring, an electronically-controlled engine for the engine information, anti-lock brakes for increased safety, and an off-board diagnostic station for servicing the electronic units. Another system would include an electronic dash for real-time feedback for the driver, similar ones for engine and brakes, and an on-board diagnostic device for self-maintenance.

The payback from information devices is knowing where the money goes and showing areas of potential savings. If a diagnostic information device provides an alert to a problem, money can be saved by correcting it before it has severe consequences.

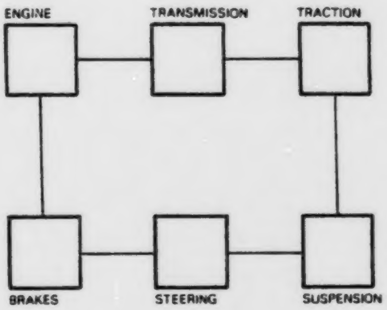
### Distribution of Functions in the Real-Time Control Area

Modules providing real-time control must provide operators with paybacks. Engine controls, limiting engine and road speed, save maintenance and fuel while anti-lock brakes may lower insurance rates. Available products in the near future include anti-lock brakes, and controls for steering, engine, transmission, suspension, and traction.

A real-time control network is needed for sharing information among systems to obtain higher performance than could be achieved individually. For example, communicating information between the transmission and engine allows for optimum shift patterns and better fuel economy. Traction control systems can be built to allow the engine to reduce torque when the wheels are slipping. Currently, there is available limited communication links between real-time control systems such as the engine and transmission.

*Exhibit 46*

***Real-Time Control Network***



Several major problems exist with a real-time control network. One is that the data must be transmitted at a high rate (one MHz), which requires a dedicated communication processor at each module and shielded cable connecting them. Another problem lies in dealing with faults in the network that cause loss of communication information. For example, if there were no information from the engine, will the transmission have backup sensors to deal with shifting, or will the system fail, possibly causing an accident?

The most promising network for highspeed communication in the '90s is the Intel/Bosch CAN (Controller Area Network) system (39). This system uses a prioritized bit-wise arbitration method for contention. It has several modes for detecting and recovering from errors and faults, e.g., CRC, acknowledgement, error counters. EMI effect is minimal using shielded twisted-pair with a differential mode transceiver (4 lines). Cost of such a system will initially be high for the communication processor and shielded twisted-pair. Intel's schedule for production quantities is in the '88-'89 period.

Current work on a high-speed communication network is being done by the SAE Truck and Bus Diesel Controls Subcommittee. The latter has adopted a dedicated link between engine and transmission for R&D work, using the dedicated J1708 compatible datalink. This is the standard that is being used to connect DDEC and ATEC.

The problem occurring when a module or a network failure causes a loss of communication needs to be resolved in the total system architecture. One method is to focus on distributed control modules that operate with lower performance independently of the high-speed network. For example, consider the case of communication between the engine and transmission controllers. The transmission controller, sensing a loss of communications, monitors both engine speed (using a separate sensor) and road speed, and shifts the transmission down or up depending on their speeds. The engine controller, detecting a faulty communication link, initiates a shift up or down when the engine speed exceeds or falls below set levels.

Integration of the different systems into one that optimizes total vehicle performance is very likely to occur in the future. In the near term, however, only limited integration will done on this level. The major drawback to integrating real-time control modules in the transit industry is the liability issue for a failure in the system. One supplier designs a component in a system for fail-safe operation without regard for another supplier (possibly a competitor), who designs another component. The transit vehicle manufacturer integrates the two components and a failure occurs. Is the problem with the supplier modules, the real-time network, or the overall system? Cooperative working relationships among selected suppliers are needed to resolve this issue. Since the industry is structured so that suppliers provide components to the majority of transit bus manufacturers, the issue does not seem likely to be resolved in the near future.

## COMPONENT MODULARITY

Modularity -- plug-in modules that could perform a variety of functions, depending on the software programming -- has often been mentioned as a key strategy to meet the varied requirements of transit operators. Current and past practice, however, has been the opposite:

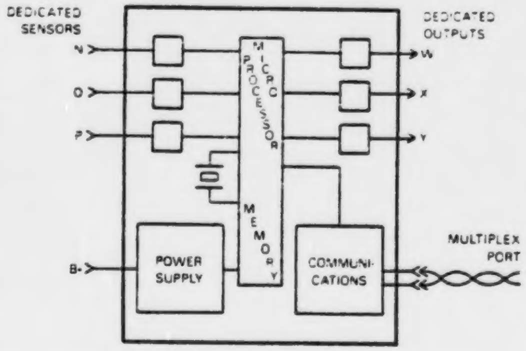
- Vehicle electronic-control modules designed over the past two decades have generally been highly specialized. Since application volumes in the transit industry have been low, the cost to design and tool custom modules are difficult to justify. Even then, quite a few custom integrated circuits have been designed and manufactured for specific urban transit electronic control module applications.
- Generally, electronic modules are mounted in the relatively environmentally protected area near the driver's seat. Achieving acceptable levels of reliability with new applications of complex electronically controlled systems has not been easy, even with control modules packaged near the driver.
- For the most part, modules have used their own set of dedicated sensors, performed their own highly specialized function and driven their own set of actuators and/or displays. Stand-alone systems have tended to be developed as the most pragmatic way to deal with organizational boundaries and a stand-alone option marketing preference on the part of manufacturers.

This practice of designing highly specialized single-purpose stand-alone systems with little or no sharing of sensor or other processed data is being seriously challenged. Technology is being driven by economic reality. The cost to design, develop, and validate new modules to increasingly stringent reliability standards for each new application is becoming very costly and time consuming. The infrastructure to handle a multitude of module requirements is becoming increasingly unmanageable.

In looking at many of these recently designed stand-alone vehicle electronic modules, many similarities are found:

- Many modules are microcomputer-based.
- The instruction set is usually contained by masked ROM, but EPROM is now frequently substituted, providing additional flexibility to accommodate fast turn around for development changes.
- The module usually contains a regulated power supply for the microprocessor and other critical circuits.
- Some kind of conditioning, demodulation, detection or A/D conversion is used for dedicated sensor inputs.
- Output switches are used to drive system actuators, or a display driver is provided for instrumentation modules.
- The module often contains a watch-dog timer to assure reset of the microcomputer.

These similarities in design indicate a trend for module hardware to become more standardized in architecture, communications and physical construction. There is also a shift from hardware to software intensive design for new applications. In fact, there is probably a potential opportunity for some very generic modules that would only require local programming of the EPROM, or other memory device, to handle a wide range of service requirements. Future evaluation of generic module solutions for vehicle control application would potentially yield the following advantages:



*Generic Control Module*

*Exhibit 47*

- Within reasonable limits, module design, packaging and tooling costs could be spread over higher volumes, providing economic advantages.
- Reliability of the module and integrated circuits could be established and hardened through extensive testing and field experience.
- Some hardware changes will still be required, but the emphasis of the design and testing of new applications will be shifted from one of hardware design to software design.

## SYSTEMS STANDARDIZATION

An important aspect of transit vehicle electronics is the evolution of standardization within the industry. The transit vehicle industry in North America produces and uses essentially customized vehicles. As more and more electronic systems become available, this tradition of customization will cause problems in the application of vehicle electronics and diagnostic systems if standardization is not an integral part of the industry.

**Overseas.** Industry cooperation is essential to realize the potential of vehicle electronics in certain areas. The European joint research project, Prometheus, is one example of such cooperation. This eight year project involves thirteen European automotive manufacturers and has a principal objective of enhancing safety through an integrated systems approach involving standardized vehicle-to-vehicle communications.

A similar Japanese project among Toyota, Nissan, Mazda, Honda and six electronics manufacturers -- Fujitsu, Nippondenso and Sumitomo included -- was announced in 1986. They have agreed to the joint development of navigation and travel control systems that will use electronics and telecommunications technologies to guide automobiles.

In the diagnostics area, a working group of the International Standards Organization (ISO TC22 SC3 WG1 Diagnostics Questions) is trying to establish a common communication format for testers and electronic control units that would appear to be similar to the ATA/SAE J1708 in North America.

**North America.** Presently, there are various SAE, ATA and TMC subcommittees and working groups which are in the process of generating such communication standards or RP's (recommended practices) which the transit industry can use.

As mentioned, a serial communications standard has been decided upon by the ATA/SAE Electronic Interface Subcommittee to help eliminate sensor duplication on trucks and buses. This standard is in the form of two SAE RP's. SAE J1708 addresses the hardware to be used with this serial communications link. It also recommends a means to transmit information in a proprietary format. SAE J1708's companion document is the SAE J1587 RP which addresses the formatting of information over the data link. THis RP is also developed by the ATA/SAE Data Format Subcommittee. It is these types of industry standards that will help the vehicle system integrators piece together the bus electronics puzzle.

Another SAE working group has recently been formed to specifically address the standardization of diesel electronic engine controls. This group will be directing its efforts toward standardization of items like pedal position sensors, instrument panel controls, vehicle speed input interfaces, and electronic engine and electronic transmission control interfaces.

Diagnostic standards in the electronic truck and bus industry are also being addressed by a working group of the Data Format Subcommittee. The purpose of this group is to work on diagnostic data format standardization which will help constrain the proliferation of non-compatible diagnostic tools.

The Electronics Interface Subcommittee is looking into a 'second generation' data link RP. This serial communications link would probably be used for control purposes as opposed to the J1708 RP which is not to be used for control type information. This high speed data link could open the door to new opportunities for electronic engine control systems.

These subcommittees and working groups are represented and supported by most all facets of the heavy duty trucking industry. It is through this involvement that useful standards can be generated and the transit industry in Canada should be contributing.

Manufacturers need cooperation among suppliers and customers. The designer needs to adhere to and participate in the development of standards such as the SAE J1708 Recommended Practice. The system integrator must be aware of the capabilities of the supplier modules and their limitations, and must strictly enforce standardization of communications between components in order to have a workable system. The vehicle builder must take an active role in assisting suppliers with system requirements. Suppliers can no longer be expected to design "stand-alone" subsystems.

Electronics are increasingly important to the transit industry. It is important that it profits from mistakes of the automobile industry, which is ahead of it. The customer has to develop a knowledge of the various black boxes, understand what they can do, and work to integrate them into a more uniform, integrated system.

# 14. DEVELOPMENT PROGRAM

An evaluation of diagnostic functions, maintenance problems and vehicle subsystems affected has indicated that the cost-effectiveness of diagnostic systems on-board transit buses is such that transit agencies should be giving more consideration to this aspect than has been the case in their future maintenance and equipment acquisition programs. As with the case with many such new technological developments, however, senior governments will probably have to lead the way with selected development and demonstration programs to advance the technology and demonstrate the effectiveness of the diagnostic systems before individual transit properties will begin making proper use of these systems.

Major concerns in the development of such a program include the interaction of the diagnostic systems with other forthcoming technological developments such as power management, multiplexing, electronic modules and other sensors and actuators. Major issues to be addressed include functional integration, feature consolidation, component modularity, systems standardization and component reliability. These issues and concerns lead to the conclusion that a strong reliance has to be placed on existing systems that are being developed in the trucking and automotive industries -- that a new comprehensive diagnostic system with its own sensors and electronic modules is not appropriate given the present well-developed state-of-the-art in transportation electronics.

In this chapter, a proposed program is outlined for the development and demonstration of a personal computer-based bus diagnostic system that would: (1) use existing technology (DDEC and ATEC), (2) utilize the ATA/SAE data communications protocol standard, (3) be expandable to include other subsystem diagnostics when available, and (4) incorporate expert type assistance in fault isolation.

## PROPOSED DEVELOPMENT CONCEPT

### Background to the Concept

Detroit Diesel Allison introduced Detroit Diesel Electronic Control (DDEC) for diesel engines in September 1985 and became the first engine manufacturer in North America to provide an electronic engine control system for the transit industry. This engine control system also offers diagnostic capabilities which can easily be expanded to meet most of the needs for diagnostics by the transit industry.

The DDEC I system, based on the General Motors Custom Microprocessor chip set, controls fuel injection timing and quantity via electronic unit injectors (EUI). This two-box system includes a dash-mounted module containing the digital electronics and an engine-mounted, fuel-cooled module with the analog injector driver components. Sensors, monitoring critical engine operating parameters, provide signals to DDEC for the microprocessor calculations. In addition to electronic fuel control and speed governing, DDEC I provided self diagnostics, engine protection diagnostics and a wide selection of application options, such as cruise control and road speed governing.

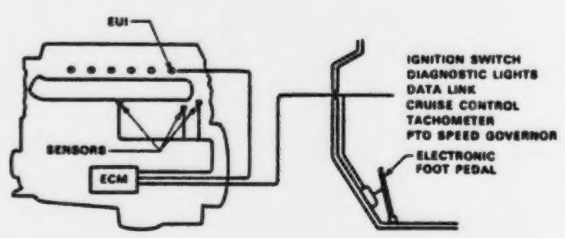
The DDEC II development took advantage of advances in technology to integrate all control system electronics into a single engine-mounted, fuel-cooled electronic control module (ECM). Using the General Motors Single Chip Microprocessor (GMSCM), it provides enhanced control system performance and additional control features as well as simplified installation.

### System Concept Overview

The major subsystems of DDEC II include the electronic unit injectors, the electronic control module, and the sensors (Exhibit 48). Fuel is delivered to the cylinders by the electronic unit injectors which are cam-driven for mechanical pressurization of the fuel and controlled via solenoid-operated valves for precise fuel delivery. The ECM computes fuel timing and quantity and actuates the electronic unit injector solenoids through high current, pulse width modulated (PWM) electronic drivers. The ECM also monitors the solenoid current to sense when the injector valve closes and uses this information to compute timing for subsequent injection events.

Exhibit 48

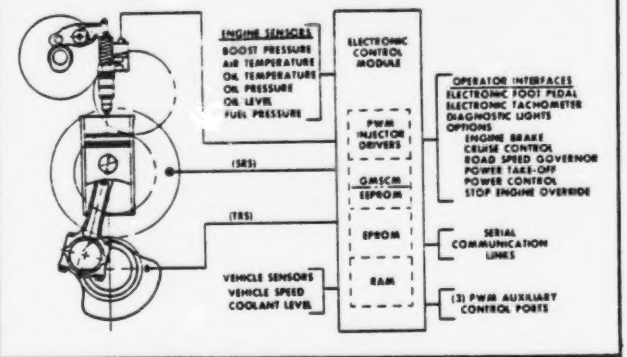
**Vehicle Installation of DDEC II**



Source: Detroit Diesel

*Exhibit 49*

**Schematic Diagram of DDEC II**


ENGINE SENSORS
BOOST PRESSURE
AIR TEMPERATURE
OIL TEMPERATURE
OIL PRESSURE
OIL LEVEL
FUEL PRESSURE
ELECTRONIC CONTROL MODULE
PWM INJECTOR DRIVERS
GMSCM
EEPROM
EPROM
RAM
(SRS)
(TRS)
VEHICLE SENSORS
VEHICLE SPEED
COOLANT LEVEL
OPERATOR INTERFACES
ELECTRONIC FOOT PEDAL
ELECTRONIC TACHOMETER
DIAGNOSTIC LIGHTS
OPTIONS
ENGINE BRAKE
CRUISE CONTROL
ROAD SPEED GOVERNOR
POWER TAKE-OFF
POWER CONTROL
STOP ENGINE OVERRIDE
SERIAL COMMUNICATION LINKS
(3) PWM AUXILIARY CONTROL PORTS

Source: Detroit Diesel

The DDEC II system is illustrated in Exhibit 49. Configured for 12 sensor inputs and 10 switch and/or specialized inputs, the module controls up to 8 injector driver outputs, 3 general-purpose pulse width modulated outputs and 6 specialized outputs. Bi-directional serial communications lines designed to the SAE J1708 recommended practice are provided.

The key inputs for fueling the engine and controlling the speed are throttle position, the sychronous reference sensor (SRS) for cylinder sequencing and the timing reference sensor (TRS) for cylinder location. Operator demand for power is requested via the electronic foot-pedal, while SRS and TRS sensors provide information on the engine crank position and speed.

## DDEC II Control Functions

The fundamental variable controlled by DDEC II is the engine fuel input. This is accomplished by the fuel pulse width and timing signals applied to the electronic unit injectors. The ECM calculates a desired torque level based on driver demand and RPM. Extensive flexibility is provided to allow desired characteristics across the speed-load plane.

The basic torque request and injection timing are modified during transients for smoke and noise control. Compressor discharge pressure and the time derivative of RPM are monitored to provide significant improvement in both smoke and noise while maximizing the transient torque response of the engine.

Six governing modes which modify the basic torque request are available to control engine and vehicle speeds: idle control, power take-off speed control, vehicle speed cruise control, engine speed cruise control, road speed limiting, and engine speed limiting. The speed control algorithms were chosen after extensive modeling and can be configured to control all known drivetrains while maximizing responsiveness to load changes. Noise and smoke is controlled while minimizing exhaust emissions. The timing is carefully controlled during engine crank to reduce start times.

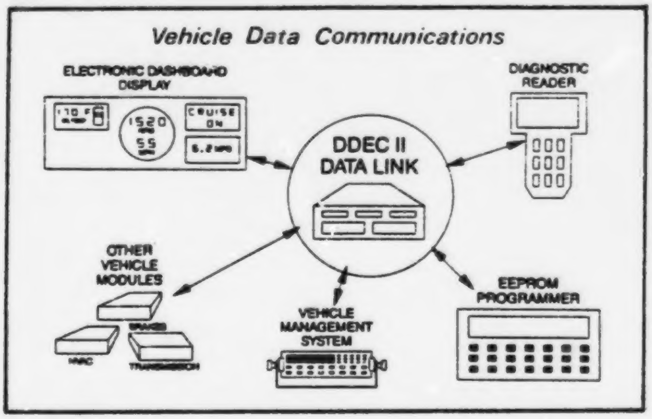
Three pulse width modulated outputs provide control for options such as glow plugs, bypass blowers, three-wheel turbines and auxiliary sensors.

## Serial Communications

DDEC II has the capability of operating two separate serial data links. One of these communication nodes is connected to the J1708 general-purpose link for the primary purpose of transmitting sensor data to other modules within the vehicle (Exhibit 50). These modules may include electronic dashboard displays, vehicle management information systems, vehicle location systems, and electronic transmissions. In addition to sensor data, other parameters available from the DDEC II system include calculated engine fuel rate and total fuel consumption, total engine hours accumulated, and engine calibration identification for diagnostic purposes.

Exhibit 50

*Vehicle Data Communications*



Source: Detroit Diesel

The general-purpose link is also used to transmit diagnostic information or perform diagnostic functions in response to requests received from external instrumentation. Requests for changes of feature and function calibration values stored in EEPROM are also received across the data link. A second data link is provided for special applications.

One area of the EEPROM is reserved for storage of data that changes during engine operation. This memory is used for the logging of accumulated engine operating hours, fuel consumption, diagnostic codes and other cumulative information. All this information can be readily accessed via the serial communication link by the DDEC II diagnostic readers or other equipment capable of accessing the data link.

## On-Board Diagnostics

The on-board diagnostic capabilities of DDEC II can be categorized into three areas: self-diagnostics, engine system protection, and engine performance diagnostics.

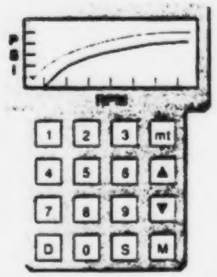
**Self-Diagnostics.** The ECM continuously performs self-checks and monitors the other system components, including the injector solenoids, sensors and wiring. System diagnostic checks are made at ignition-on and continue throughout all engine operating modes. When a fault is detected and exists for more than two seconds, the ECM illuminates the dashboard 'Check Engine' light to alert the vehicle operator of the malfunction and also stores the appropriate diagnostic code in EEPROM memory.

**Engine System Diagnostics.** In addition to health monitoring of various system components, the electronic control module (ECM) also compares the sensor outputs against calibration high and low limits for the current engine operating speed. The engine protection diagnostics for loss of oil pressure, oil over-temperature and low coolant level can prevent a minor problem from becoming a major failure with its attendent costs. If one or more of these parameters falls outside of the safe limits, the 'Check Engine' and the 'Stop Engine' lights are turned on to warn the operator that a potential engine-damaging malfunction has been detected. At the same time, the appropriate diagnostic code is logged in EEPROM memory. In addition, an audit trail is made of the event(s) for retrieval during servicing and maintenance.

**Engine Performance Diagnostics.** The portable diagnostic readers also provide for diagnosing engine performance problems not directly related to faults in the DDEC system. The DDEC system, by itself, has already eliminated many mechanical problems associated with low power complaints. These include elimination of mechanical adjustment of injector timing, governor linkages, governor spring settings and mechanical foot pedal to engine linkages. A major tool in diagnosing low power complaints in the DDEC system is the cylinder cut-out technique.

*Exhibit 51*

*DDEC II Diagnostic Data Reader*



FEATURES
- LCD DISPLAY
- BATTERY OPERATION
- PROGRAM CARTRIDGES
- ENGLISH/METRIC UNITS
- OPTIONAL RS 232 PORT

FUNCTIONS
- DISPLAY DIAGNOSTIC CODES/DESCRIPTION
- DISPLAY SENSOR OUTPUT
- PROVIDES CONTROL OF:
  - ENGINE RPM
  - FUEL RATE
  - BEGINNING OF INJECTION
  - SMOKE CONTROL ENABLE/DISABLE
  - CYLINDER CUT-OUT

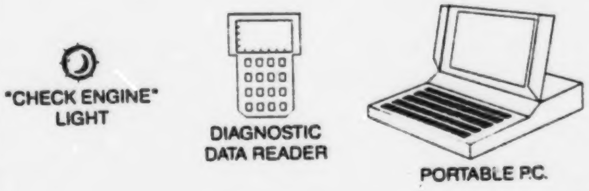
TYPICAL GRAPHIC DISPLAYS
- SENSOR OUTPUT VS. RPM
- SENSOR OUTPUT VS. TIME
- CYLINDER CUT-OUT PULSE WIDTH

Source: Detroit Diesel

The hierarchy of diagnostic tools is illustrated in Exhibit 52. In engineering development, personal computers have been programmed to communicate with the engine via the serial data link. This configuration provides more elaborate diagnostic software routines for data collection and evaluation. For example, special computerized manual-type trouble-shooting or expert-type assistance in fault isolation and repair could be built into the personal computer programs. It is also conceivable that real-time engine data can be transmitted from the field to the Detroit Diesel Engineering Center for assistance in diagnosing faults.

*Exhibit 52*

*Hierarchy of Diagnostic Tools*



Source: Detroit Diesel

## TECHNICAL DEVELOPMENT APPROACH

The primary objectives of the proposed program are the development and demonstration of an automated diagnostic system for transit buses with the DDEC II/ATEC I powertrain. Automated daily inspections and service maintenance tests would provide for:

- Early detection of powertrain malfunctions permitting scheduling of maintenance and avoidance of road calls.
- Standardization of service maintenance procedures.
- Improved diagnostic and fault isolation techniques.
- Improved record-keeping with both current status and historical unit information for prognostic and performance or efficiency ratings.

The bus powertrain diagnostic system will be automated through the use of IBM-compatible personal computers, and a data translator for interfacing the powertrain ECM's to the computer's RS232 serial port. The translator would be installed as part of the personal computer test station and would be installed on a specific bus only for special tests.

Software would be developed for bidirectional communications between the personal computer and the powertrain controllers; and record keeping and report formatting will utilize commercially available personal computer software such as DBase. The personal computer approach offers increased software flexibility and eliminates the added costs and time associated with the development of specialized data recorders. The personal computer CRT displays also provide for graphical displays and operator prompt messages. Advantage will be taken of the EMC diagnostic capabilities and the compliment of sensors that are integral to both the engine and transmission systems.

The proposed system provides for the collection and analysis of powertrain parametric and diagnostic information without the need for installation of special sensors or other electronic hardware on individual buses. Daily automated inspections, with pass/fail tests, will aid in minimizing road call service and provide the unit database for prognostic and service repairs. Service repairs will benefit from historical service information, improved fault isolation and confirmation of repairs.

The translator will be developed with four spare analog inputs which can be used for other subsystem sensors. Real-time data acquisition from buses operating in revenue service will also be available. On-board data collection, using a data translator, would be utilized only when it is deemed necessary to collect additional information for resolution of intermittent or transient faults. Data collected, during road testing, would be downloaded to the personal computer database for post-trip analysis. The overall system will be designed and implemented so as to require a minimum of special training for service personnel.

Although the proposed program includes the development of database files for each test bus, it is not the intention of this proposal to provide a bus fleet management information system. Any interfacing with centralized computer systems would be outside the scope of this proposal and the responsibility of the transit fleet operation. For the period of the demonstration, it is proposed that data file transfers utilize standard personal computer phone modem software unless other systems are already operational and could provide for these needs.

## APPLICATION OF THE SYSTEM CONCEPT

The automated bus powertrain diagnostic system will consist of two stations: Daily Service and Service Maintenance.

### Daily Inspection Station

The Daily Inspection Station will perform automated pass/fail tests, record specific powertrain sensor data, and flag abnormal events that occurred during the previous period of revenue operation. Exhibit 53 lists typical information that will be recorded during the daily testing.

*Exhibit 53*

**Daily Test Information**

- Bus Identification No.
- Engine Total Hours
- Date/Test Time
- Active Diagnostic Codes
- Timed Codes
- Engine Serial No.
- Engine Idle Hours
- Total Fuel Used (Gals)
- Historic Diagnostic Codes
- ECM Battery Voltage
- Typical automated tests ...
    - Cylinder cutout (individual cylinder power checks)
    - Injector solenoid response time
    - Engine sensor data vs RPM
    - Engine acceleration/deceleration tests
    - Stall speed testing (at selected intervals)

The number and type of automated testing for daily powertrain inspections will be part of the overall program development and evaluation demonstrations. The addition of other sensors, such as for checking engine and transmission oil levels, will be considered if cost effective and reliable sensors can be obtained.

The special equipment for the Daily Inspection Station includes an IBM-compatible personal computer, a data translator, personal computer software, phone modem and cabling to connect the translator to a readily accessible diagnostic connector on the bus. A personal computer printer will also be required if hard copy exception reports are required.

The degree of operator intervention during the daily inspection testing will be based on safety needs. The connection of the translator to the bus diagnostic connector can request the transmission to select 'neutral' position, prompt the operator to apply the bus brakes and confirm that these actions have been implemented. Initiation of testing would also probably require operator input to insure that conditions are 'SAFE' to proceed with command requests to operate the engine test sequences. Once testing has been initiated, the overall test time will be approximately 3 minutes.

### Service Maintenance Station

The Service Maintenance Automated Bus Powertrain Diagnostic System would provide for:

- Diagnosis of faults reported by the bus driver or from the daily inspection reports.
- Performance of specific tests during routinely scheduled vehicle inspections; with pass/fail reporting. Graphical displays on the personal computer CRT will assist the mechanic by providing out-of-tolerance indicators.
- Quality control tests to insure that proper maintenance has been performed prior to re-scheduling of the bus in revenue service.
- Standardization of diagnostic procedures.
- Real-time displays of multiple powertrain parameters such as RPM, oil pressure, coolant temperature, etc.
- Real-time displays for adjustment of door interlock switches (on/off indication), high idle RPM, etc.
- Development of unit history files for future pass/fail tests, prognostic and management performance or efficiency reporting.

For the demonstration period, it would be proposed that database files be transmitted between the Daily Inspection and Service Maintenance Stations via personal computer phone modem (unless centralized computer data transfer can be implemented by the bus fleet personnel). The daily inspection report data would be utilized to assist the mechanic in diagnosis, fault isolation and confirmation of repair. The special equipment required at the Service Maintenance Station would duplicate that outlined for the Daily inspection Station.

The initial software package for the Service Maintenance Station will emulate the DDEC/ATEC diagnostic reader and provide expanded information for the diagnostic codes. During the demonstration period, the software capabilities will be extended to utilize the database information in assessing the performance of the powertrain being tested, and offer recommended sequences for diagnosis of multiple faults. Where possible, test sequences will be automated, but will allow mechanic intervention to bypass specific tests or select alternate test sequences.

During the program, software development would be upgraded to include such features as a 'Computerized Trouble-shooting Manual' and 'Expert' type assistance in fault isolation and repair.

Hard copy report formats can be developed and modified throughout the program within the limits of the selected personal computer database software.

The selection of the demonstration test requires that the bus fleet include buses which have the DDEC II/ATEC I powertrain. Within six months of the program initiation, personal computer software will be available to perform the basic functions outlined for both test stations. This would cover limited automated testing, and CRT displays of powertrain parametric data plus database files for individual buses. Personal computer terminals, cabinets and other equipment would be procured and installed at that time.

At the end of the first year of the program, automated tests would be defined and ready for beta testing. Development of selected automated tests would continue throughout the second year of the program with software updates provided when significant. The computerized trouble-shooting guide with 'expert' assistance would be finalized during the second year of the program. To assist in overall software development, database files for all test buses could be periodically transmitted via phone modem to Detroit Diesel for analysis.

The results of the proposed development program would be a personal computer based bus diagnostic system that would incorporate expert type assistance in fault isolation and would be based on existing well-developed technology using the ATA/SAE data communications protocol standard to ensure compatibility and integration with other potential systems.

To implement the proposed program will require some cooperation between provincial and federal transportation agencies and the assistance of an urban transit property that currently is purchasing or has purchased some buses that are equipped with DDEC II and ATEC I.

## CONCLUSIONS AND RECOMMENDATIONS

The report outlines the results of the investigation into current maintenance practices and the state-of-the-art of vehicle diagnostic systems. It is noted in the report that the state-of-the-art is well advanced, but that the operators are unsure of the benefits to be achieved of any new system that would require vehicle retrofits. Newer, integral systems that are being built into engine and transmission components appear to be more acceptable to the transit industry -- that is, the market appears to be driven by suppliers and as a fallout of new trucking technologies. Therefore, it is concluded in this report that:

- **Vehicle diagnostic systems are applicable and beneficial to the urban transit industry if they are an integrated aspect of other systems such as electronic engine controls and electronic transmission controls.**

In the trucking industry, a standardized communication system has been developed by a joint committee of the ATA/SAE to join together different electronically-operated vehicle systems. This standard protocol for electronic components has received practically 100 percent backing by the manufacturing industry and is a driving force behind new systems developments. Therefore, it is recommended that:

- **The transit industry, through the Canadian Urban Transit Association, should monitor these ATA/SAE developments closely and, possibly, develop their own (albeit very similar) communication protocols.**

The fallout from the trucking industry from integrated electronic components will probably affect the transit industry more than the development of any transit-specific on-board health monitoring systems. But the transit industry has to start preparing themselves for these changes. In order to do this, a development program is proposed that builds on current developments with electronic engine and transmission controls with integral diagnostic capabilities and incorporates software development to meet Canadian needs. Therefore, it is recommended that:

- **Federal and provincial transportation authorities cooperate to undertake a demonstration of a PC-based bus diagnostic system that would incorporate expert type assistance in fault isolation and that would be based on existing well-developed technology (such as DDEC and ATEC) using the ATA/SAE data communications protocal standard.**

It must be recognized, however, that the Canadian transit industry in general needs to develop better and more standardized maintenance cost information. Due to different methods of categorizing and aggregating data, it is presently difficult to compare costs between properties. Therefore, a final recommendation is that:

- **As transit properties in Canada computerize their maintenance reporting functions and, as better data becomes available, this data should be re-applied to the diagnostic cost savings models in this report.**

# REFERENCES

1. Wood, Peter. "A Knowledge-Based System for Transit Bus Maintenance". Transportation Research Record 1019, Transportation Research Board, Washington, D.C. pp 85-90.
2. Applied AI Systems and Cognos Inc. "Expert Systems: Their Application in the Canadian Transportation Sector". Prepared for Transport Canada Research & Development, Ottawa, Ont. January 1986.
3. Canadian Urban Transit Association. "Transit Research Outlook for 1986". Presentation at the 81st Annual Meeting of the Canadian Urban Transit Association, Vancouver, B.C. June 1986.
4. Zimmerman, Joseph F. "Transit Maintenance in New York State: Issues and Analysis". Transportation Research Record 1066, Transportation Research Board, Washington, D.C. 1986. pp 1-6.
5. Jhaveri, D.R. "When Should Rolling Stock be Replaced?" Transit Journal, Volume 4, Number 4, Fall 1978. pp 61-78.
6. Robeznieks, A.R. "Design Parameters for Bus Storage and Maintenance Facilities as Related to Urban and Inter-Urban Transit Systems". Presentation at the 1978 Annual Conference of the Roads and Transportation Association of Canada, September 1978. 25p.
7. The Mitre Corporation. "Bus Maintenance Facilities: A Transit Management Handbook". Prepared for the Urban Mass Transportation Administration, Washington, D.C. November 1975. 137p.
8. University of Illinois. "Management Tools for Bus Maintenance: Current Practices and New Methods". Prepared for the Urban Mass Transportation Administration, Washington, D.C. May 1983. 73p.
9. Runkel, M. "Tasks, Organisation and Equipment of Depots and Workshops". UITP Revue, Volume 27, Number 4, 1978. pp 279-283.
10. Giuliani & Associates. "Bus Inspection Guideline". NCTRP Special Report Synthesis 10. Transportation Research Board, Washington, D.C. June 1987. 73p.
11. University of Oklahoma. "Bus Fleet Management Techniques Guide". Prepared for the Urban Mass Transportation Administration, Washington, D.C. August 1985. 313p.
12. Pake, B.R., M.J. Demetsky and L.A. Hoel. "Application of a Transit Maintenance Management Evaluation Procedure". Transportation Research Record 1066, Transportation Research Board, Washington, D.C. 1986. pp 13-21.

13. Wheeler, C. "Results of Questionnaire 83-8: Current Status and Future Development of Computer Applications". Canadian Urban Transit Association, Toronto, Ontario. March 1984. 23p.

14. Doke, John. "Fleet Management". McGraw-Hill Book Company, New York, N.Y. 1984. p118.

15. Rueda, A. and F. Miller. "A Comparative Analysis of Techniques for Determining Transit Bus Maintenance Intervals for Components". Prepared by the University of Illinois at Chicago for the Urban Mass Transportation Administration, Washington, D.C. 1982.

16. Kelly, A. "Maintenance Planning and Control". Butterworths Book Company, London, England. 1984.

17. Drake, R.W. and D.W. Carter. "Public Transit Bus Maintenance Manpower Planning". NCTRP Report 10, Transportation Research Board, Washington, D.C. December 1984. 56p.

18. Drake, Richard W. and Douglas W. Carter. "Evaluation of Bus Maintenance Manpower Utilization". Transportation Research Record 1019, Transportation Research Board, Washington, D.C. pp 49-61.

19. Singh, C. and M.D. Kankam. "Reliability Data and Analysis for Transit Vehicles". Ontario Ministry of Transportation and Communications, Systems Research and Development Branch, Downsview, Ontario. RR217. January 1977.

20. Canadian Urban Transit Association. "1985 Urban Transit Facts in Canada". Canadian Urban Transit Association, Toronto, Ontario.

21. Wolber, W.G. and B. Chicot. "Sensors for Heavy-Duty Trucks Examined". Automotive Engineering, August 1981. pp 50-55.

22. TransVision Consultants Ltd. "Microelectronics and Urban Transit". Prepared for the Transportation Development Centre in cooperation with the Canadian Urban Transit Association, Montreal, Quebec. March 1984.

23. Goldsack, Paul J. "Automatic Vehicle Monitoring in Europe". Mass Transit, Volume 13, Number 11, November 1986. pp 10-11.

24. Charlesworth, James. "How Alarm and Shutdown Systems Can Keep Our Fleet Running." Commercial Carrier Journal, January 1987. pp 95-100.

25. List, B.H. "TI View of Automotive Engine Control -- A System Approach". Convergence 78: Proceedings of the International Conference on Automotive Electronics. Society of Automotive Engineers, Warrendale, Pennsylvania. September 1978. pp 44-50.

26. Hames, R.J. et al. "DDEC II - Advanced Electronic Diesel Control". Transportation Electronics: Proceedings of the International Congress on Transportation Electronics. Society of Automotive Engineers, Warrendale, Pennsylvania. October 1986. pp 151-160.

27. Hames, R.J., R.D. Straub and R.W. Amann. "DDEC Detroit Diesel Electronic Control". Presentation at the SAE International Congress & Exposition, Detroit, Michigan, March 1985. SAE Paper 850542. 10p.

28. Schroeder, Earl J. "Allison High Tech Automatics for the '80s". Bus Ride Magazine, September 1984. pp 66-68.

29. Chew, D. "The Development of Vehicle Condition Monitoring and Fault Diagnosis Equipment for Commercial Vehicle Fleets". Proceedings of the International Conference on Vehicle Condition Monitoring and Fault Diagnosis, Institute of Mechanical Engineers, London, England. March 1985. pp. 75-86.

30. Fox, T.B. "Operating Experience With a Vehicle Fault Diagnosis System". Proceedings of the International Conference on Vehicle Condition Monitoring and Fault Diagnosis, Institute of Mechanical Engineers, London, England. March 1985. pp. 109-114.

31. United Technologies. "Automatic Bus Diagnostic System". United Technologies Hamilton Test Systems.

32. Salter, Richard G. "The Use of Microcomputers to Improve Army Ground Vehicle Readiness". Prepared by the Rand Corporation for the Defense Advanced Research Projects Agency, Department of Defense, Arlington, Virginia. March 1980. 46p.

33. Mills, G.F. and K.A. Wolf. "A Method for Evaluating Diagnostic Aid Systems in Army Land Vehicle Maintenance". Prepared by the Rand Corporation for the Defense Advanced Research Projects Agency, Department of Defense, Arlington, Virginia. April 1978. 122p.

34. Rivard, J.G. "Automotive Electronics in the Year 2000". Transportation Electronics: Proceedings of the International Congress on Transportation Electronics. Society of Automotive Engineers, Warrendale, Pennsylvania. October 1986. pp 1-18.

35. Krugler, A.D. "Vehicle Electronics -- Proliferation and Consolidation in the 1990's". Transportation Electronics: Proceedings of the International Congress on Transportation Electronics. Society of Automotive Engineers, Warrendale, PA. October 1986. pp 143-149.

36. Dick, Jerry et al. "Tomorrow's Trucks: The Users' Perspective". Presentation at the SAE Truck & Bus Meeting and Exposition, Chicago, Illinois. SAE Technical Paper 852330. December 1985. 20p.

37. Hayes, R.G. and G.W. Magginson. "Electronic Braking Systems". Convergence 78: Proceedings of the International Conference on Automotive Electronics. Society of Automotive Engineers, Warrendale, Pennsylvania. September 1978. pp 111-113.

38. Florence, D.E. et al. "Integrated Vehicle Electronics -- An Overview of Its Potential". Transportation Electronics: Proceedings of the International Congress on Transportation Electronics. Society of Automotive Engineers, Warrendale, PA. October 1986. pp 33-38.

39. Bishel, Richard A. "Integration of Truck Electronics: A Look at the '90s". SAE Automotive Engineering. February 1988. pp 115-119.

40. SAE Recommended Practice. "Serial Data Communications Between Microcomputer Systems in Heavy Duty Vehicle Applications -- SAE J1708 JAN86". Report of the Truck and Bus Electrical Committee approved January 1986. 1987 SAE Handbook, Volume 4. Published by the Society of Automotive Engineers, Warrendale, Pennsylvania.

41. Bishel, Richard A. "Maximizing Utilization of the SAE J1708 Serial Data Communication Link". Transportation Electronics: Proceedings of the International Congress on Transportation Electronics. Society of Automotive Engineers, Warrendale, Pennsylvania. October 1986. pp 287-299.

# Appendix A:
# SUMMARY MAINTENANCE DATA

# Maintenance Data for SERVICE/CLEANING

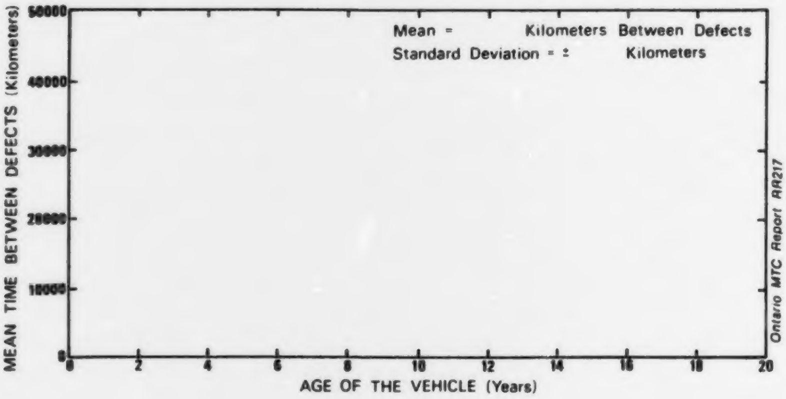
The amount of labour-hours spent on servicing and cleaning is a function of the amount of time required to perform each activity and the number of vehicles serviced and cleaned. Variations between properties are largely due to the frequency of activities. There are usually three primary activities for servicing and cleaning staff: daily servicing, major interior cleaning, and chassis wash. Of the three, daily servicing accounts for the majority of staff time. This function accounted for 23% of labour-hours and about 17% of the total costs. Annual costs are estimated at $4,320 per vehicle.

### Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | n/a | n/a | 98 |
| MTTR (Hours) | n/a | n/a | n/a | 0.20 |
| Hours/100.000 Kms | 213.0 | n/a | n/a | 206.9 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 111.2 | n/a | n/a | 108.0 |
| Number of Defects | n/a | n/a | n/a | 534.7 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $5.712 | $4.320 |
| Parts and Materials | n/a | n/a | $ 0 | $ 0 |
| Total Maintenance Cost | n/a | n/a | $5.712 | $4.320 |

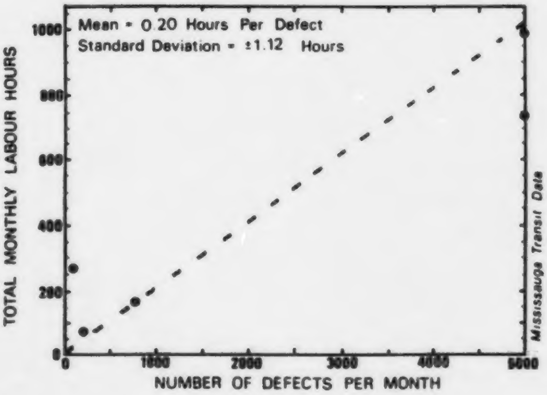
### Components

### Reliability Measure (Mean Time Between Defects)



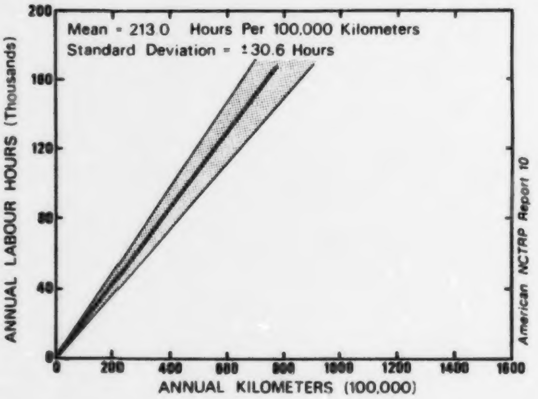
Ontario MTC Report RR217

### Repair Time (Mean Time To Repair)



Mississauga Transit Data

### Manpower Utilization (Labour Hours)



American NCTRP Report 10

# Maintenance Data for BUS INSPECTIONS

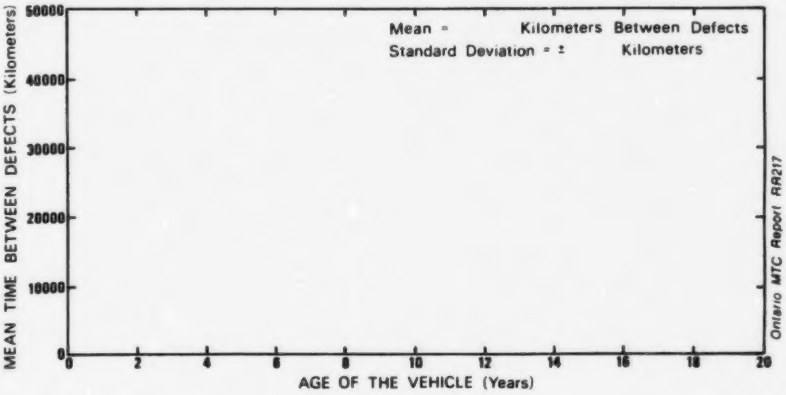
The inspection function generally consists of some type of inspection (e.g., safety, seasonal, minor, major, and statutory) and some amount of repair time. On the average, inspections account for 15.8% of total maintenance labour-hours but varies significantly by property. The primary reason for differences is local maintenance philosophy regarding inspection. Some properties devote 50 percent of inspection time to running repair, whereas others allow no running repairs during inspections. Inspections account for 12.1% of the total cost and about $3,070 is spent annually on each vehicle.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | n/a | n/a | 1,303 |
| MTTR (Hours) | n/a | n/a | n/a | 1.85 |
| Hours/100,000 Kms | 148.9 | n/a | n/a | 142.2 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 77.7 | n/a | n/a | 74.2 |
| Number of Defects | n/a | n/a | n/a | 40.1 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $ 1,719 | $2,970 |
| Parts and Materials | n/a | n/a | $ 0 | $ 100 |
| Total Maintenance Cost | n/a | n/a | $1,719 | $3,070 |

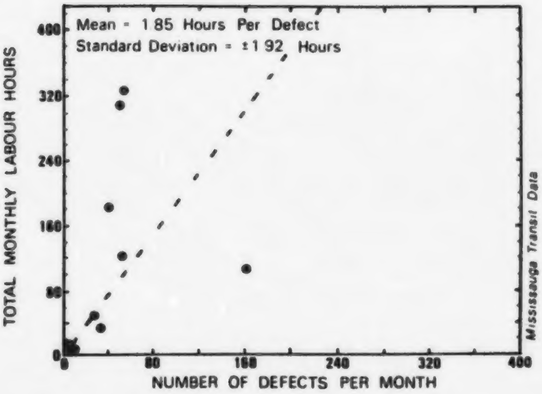
## Components

## Reliability Measure (Mean Time Between Defects)



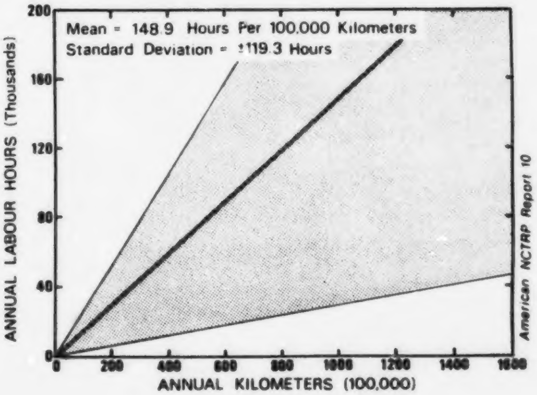
*Ontario MTC Report RR217*

## Repair Time (Mean Time To Repair)



*Mississauga Transit Data*

## Manpower Utilization (Labour Hours)



*American NCTRP Report 10*

# Maintenance Data for BODY REPAIRS

The body subsystem of the transit vehicle is composed of running repair and major repair to body, painting, upholstery, and glass. Accidents are a significant factor driving body labour-hour requirements. Body repairs are estimated to account for 14.1% of total labour-hours. The amount of labour-hours devoted to body repair is a function of vehicle kilometers (i.e., exposure), accident rates, and policy regarding acceptable vehicle appearance. Body repairs are estimated to cost about $3,490 each year per vehicle and this is 13.7% of the total annual costs.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 5.285 | n/a | 1.399 |
| MTTR (Hours) | n/a | n/a | n/a | 1 76 |
| Hours/100,000 Kms | 136.1 | n/a | n/a | 126.5 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 71.0 | n/a | n/a | 66.0 |
| Number of Defects | n/a | 9.9 | n/a | 37.3 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $1,880 | $2,640 |
| Parts and Materials | n/a | n/a | $ 480 | $ 850 |
| Total Maintenance Cost | n/a | n/a | $2,360 | $3,490 |

## Components

**Body**

- Body Paint •
- Body Work
- Painting
- Destination Signs
- Route Signs
- Run Numbers
- Wiper Motors
- Wiper Arms
- Wiper Piping
- Wiper Control

Wiper Adjustment

Windshield Washers

Engine Splash Pans

- Engine Door
- Baggage Door

Sun Visor

Driver's Blind

- Converter Door
- Fuel Filler Door

Water Filler Door

Broken Mirrors

Seat Frames

Seat Patches

Seat Back and Cushions

- Luggage Cords

Circulating Pump Covers

Door Motor

Roller and Guide

- Hinges

Treadle Mats

Interlocks

Sensitive Edge and Alarm

Operating Rods

Door Wiring

Circuit Breakers

- Control Valves

Micro Switches

Relays or Switches

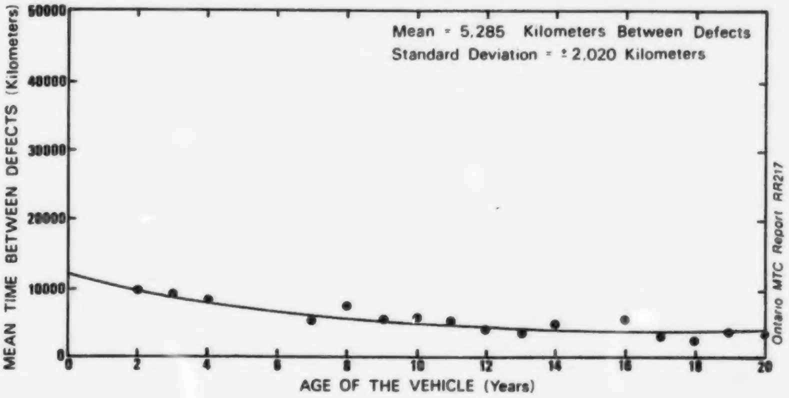
Adjustment or Lubrication

- Magnet Valve and Piping

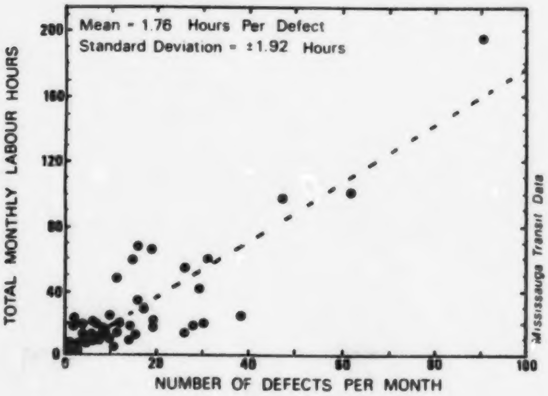
Solenoid and Diode

Door Spring

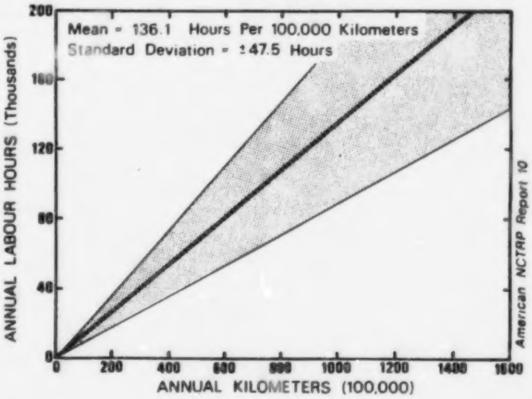
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for ENGINE AND FUEL

The engine and fuel system consists of repair, removal and replacement, and rebuild times for all engine and fuel system components. Engine and fuel labour-hours account for about 10.8% of maintenance labour-hours. Most of the variation between properties is accounted for by vehicle type. The remaining variation may be the result of mechanic training, facility efficiency, and contracting provisions. About 9.5% of the total annual maintenance cost of a vehicle is attributable to engine and fuel. This is about $2,410 per vehicle per year.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 7.644 | n/a | 3.504 |
| MTTR (Hours) | n/a | n/a | n/a | 3.40 |
| Hours/100,000 Kms | 97.6 | n/a | n/a | 97.1 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 50.9 | n/a | n/a | 50.7 |
| Number of Defects | n/a | 6.8 | n/a | 14.9 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $3.072* | $2,030 |
| Parts and Materials | n/a | n/a | $1,308* | $ 380 |
| Total Maintenance Cost | n/a | n/a | $4,380* | $2,410 |

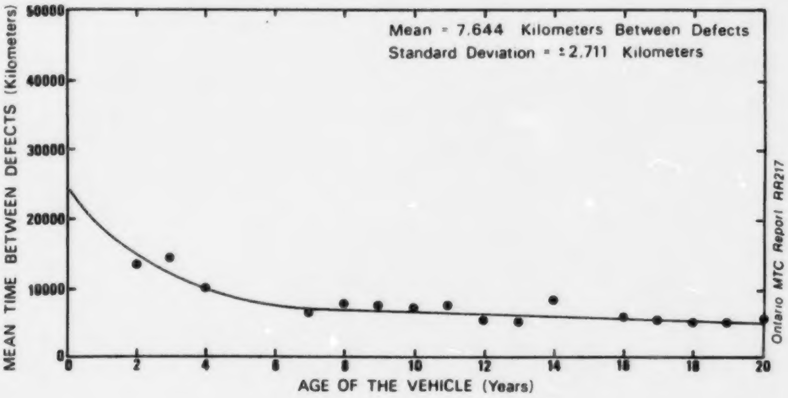
* Includes Cooling and Heating

## Components

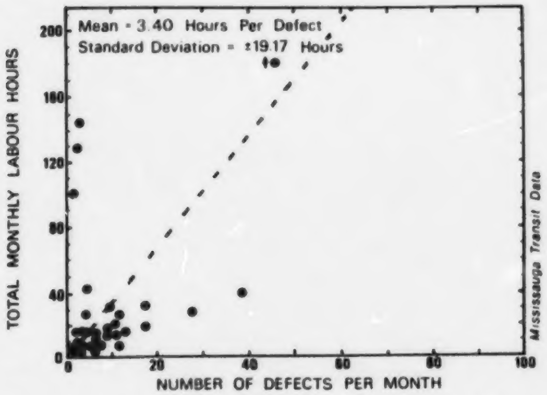
Engine

- Valves
- Oil Seals
- Engine Stop
- Skimmer Valve
- Cylinder Head
- Cylinder Block
- Blower
- Head Gasket
- Oil Sending Unit
- Bearings
- Oil Filter
- Timing Chain
- Broken Piston
- Engine Mounting
- Crankshaft Oil Seal
- Emergency Stop
- Air Cleaner
- Oil Pump
- Oil Cooler
- Oil Pan
- Damper
- Adjust Idle
- Oil Pressure Indicator
- Exhaust Pipe and Muffler
- Exhaust Manifold
- Seized Engine
- Oil Lines
- Short of Oil
- Engine Governor
- Throttle Linkage
- Governor Cap
- Accelerator Linkage
- Rocker Cover
- Out of Fuel
- Accelerator Return Spring
- Fuel Pump
- Fuel Lines
- Fuel Tank
- Vapor Lock
- Accelerator Bell Crank
- Injectors
- Injector Pump
- Adjustments
- Oil Gauge

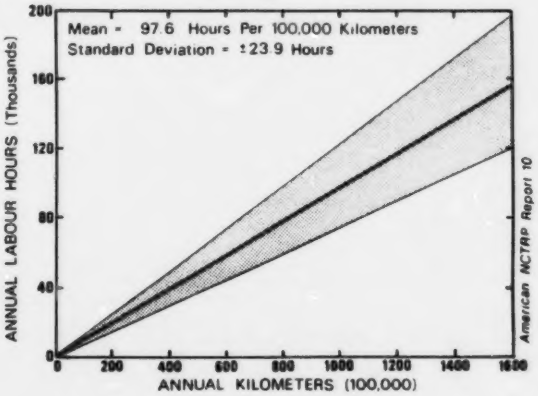
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for BRAKING SYSTEM

The braking system is made up of running repair and reline work applied to the parking brake and the front and drive axles of buses. Braking labour-hours account for 8.8% percent of the total. The primary factors driving differences between properties are kilometers of operation, route speed, and vehicle type. Properties with hilly terrain should have higher values than agencies with flat terrain. Other variables, including mechanic skill and training and facility and support equipment, may also contribute to differences. Braking accounts for 12.7% of costs and are about $3,240 per vehicle per year.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 6.879 | n/a | 3.033 |
| MTTR (Hours) | n/a | n/a | n/a | 2.40 |
| Hours/100,000 Kms | 76.7 | n/a | n/a | 79.3 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 40.0 | n/a | n/a | 41.4 |
| Number of Defects | n/a | 7 6 | n/a | 17.2 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $2.960* | $1.660 |
| Parts and Materials | n/a | n/a | $1.036* | $1.580 |
| Total Maintenance Cost | n/a | n/a | $3.996* | $3.240 |

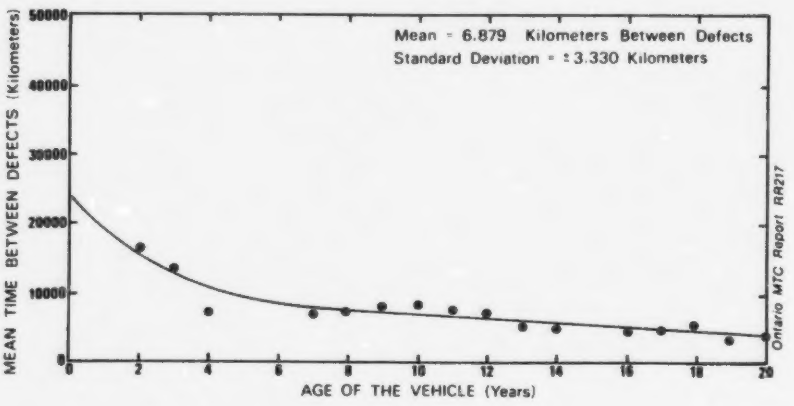
* Includes Air System

## Components

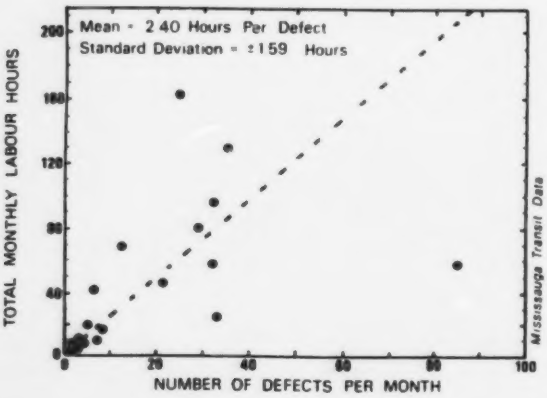
**Brakes**

- Adjustments
- Brake Cams
- Brake Linkage
- Slack Adjuster
- Roller in Wheel
- Handbrake
- Brake Relining
- Drums
- Maxi Brake
- Brake Chamber
- Brake Cylinders or Diaphragms
- Application Valve
- Release Valve
- Brake Relay
- Brake Pedal

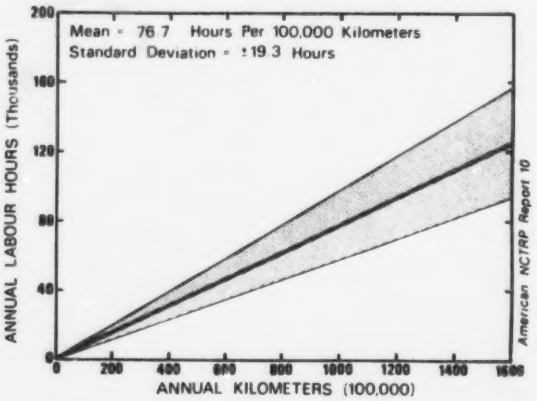
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for ELECTRICAL SYSTEM

The electrical system is made up of running repair, removal and replacement, and rebuild activities for starters, alternators and generators, batteries, and miscellaneous electrical components. Overall, electrical work accounts for 9.1 percent of total maintenance costs and 7.2 percent of total labour hours. Differences between transit properties is primarily attributable to vehicle-kilometers and vehicle type, although climate an average speed may have minor impacts. The total annual cost for the electrical system maintenance per vehicle is estimated at $2,310.

## Compiled Maintenance Measures

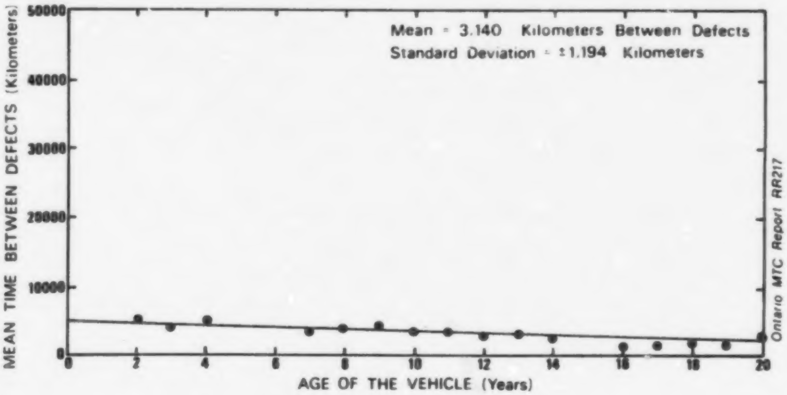
| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 3.140 | n/a | 1.467 |
| MTTR (Hours) | n/a | n/a | n/a | 0.95 |
| Hours/100,000 Kms | 57.8 | n/a | n/a | 64.8 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 30.2 | n/a | n/a | 33.8 |
| Number of Defects | n/a | 16.6 | n/a | 35.6 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $1.477 | $1,350 |
| Parts and Materials | n/a | n/a | $ 427 | $ 960 |
| Total Maintenance Cost | n/a | n/a | $1.904 | $2,310 |

## Components

**Electrical System**

Speedometer
Tachometer
– Speedo Sending Units
– Speedo Adaptor
– Circuit Breaker
– Starter and Components
Switches
Wiring
– Starter Relay
– Generator
– Alternator
– Voltage Regulator
– Rectifier
– Generator Relay
Odometers
– Generator Indicator
– Battery
– Loose Connections
– Light Fixtures
Sockets
Power Pack/Invertor
Passenger Buzzer
Master Switch
Horn and Relay
Register
P.A. System
Generator Belts

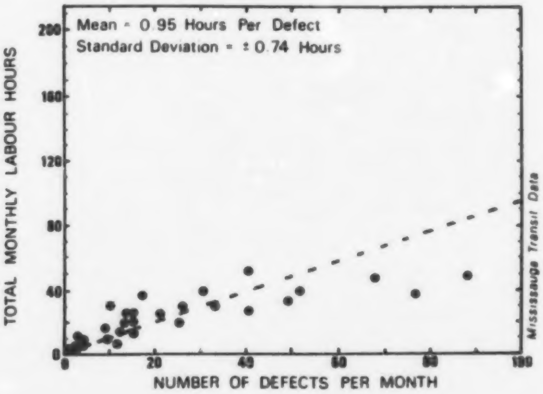
## Reliability Measure (Mean Time Between Defects)



Mean = 3.140 Kilometers Between Defects
Standard Deviation = ±1.194 Kilometers

Ontario MTC Report RR217

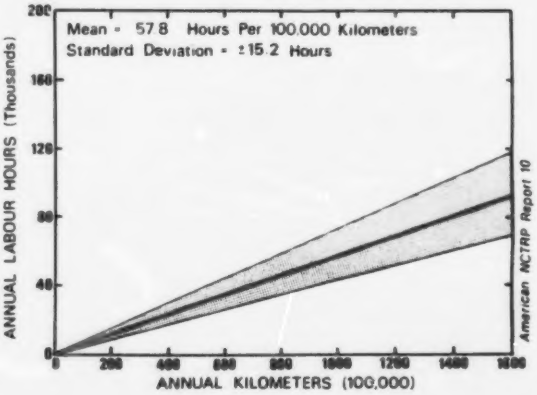
## Repair Time (Mean Time To Repair)



Mean = 0.95 Hours Per Defect
Standard Deviation = ± 0.74 Hours

Mississauga Transit Data

## Manpower Utilization (Labour Hours)



Mean = 57.8 Hours Per 100,000 Kilometers
Standard Deviation = ±15.2 Hours

American NCTRP Report 10

# Maintenance Data for TRANSMISSION

The transmission and drivetrain is made up of running repair, removal and replacement, and rebuild work on the transmission and differential. Tearing down, cleaning, and rebuilding of small accessories are also included here. Overall, the drivetrain system is estimated to account for 5.8 percent of total maintenance labour-hours. About 27 labour-hours are spent each year. Differences between properties are probably a function of vehicle-kilometers, transmission type and vehicle speed. Annual costs for the transmission and drivetrain are about $2,000 or 7.8 percent of the total costs.

## Compiled Maintenance Measures

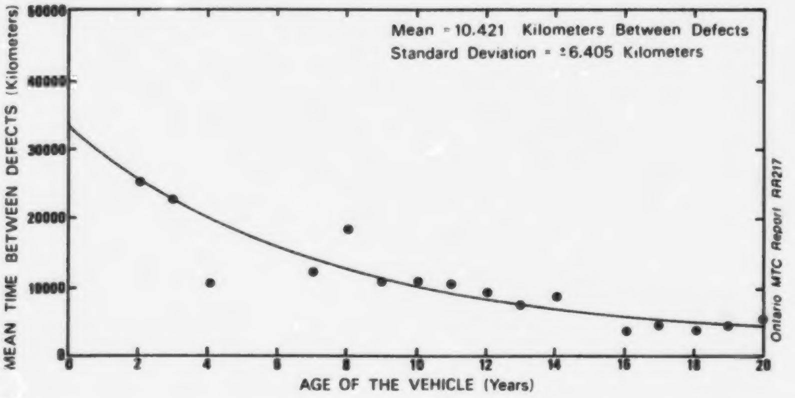
| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 10.421 | n/a | 6.188 |
| MTTR (Hours) | n/a | n/a | n/a | 3.25 |
| Hours/100.000 Kms | 45.4 | n/a | n/a | 52.5 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 23.7 | n/a | n/a | 27.4 |
| Number of Defects | n/a | 5.0 | n/a | 8.4 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $1.590 | $1,100 |
| Parts and Materials | n/a | n/a | $1,137 | $ 900 |
| Total Maintenance Cost | n/a | n/a | $2.727 | $2.000 |

## Components

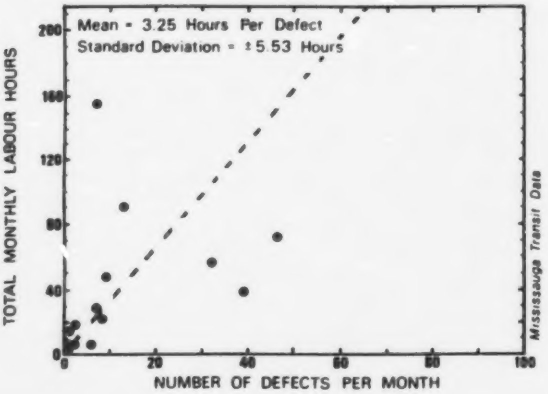
Transmission

- Convertor Pump
- Solenoid and Wiring
- Convertor Oil Lines
- Convertor Cooler
- Convertor Check Valve
- Convertor Oil Switch
- Topped Up Fluid
- Throttle Dip Cylinder
- Gear Selector Linkage
- Transmission
- Selector Forks
- Shift Lever
- Gaskets
- Convertor
- Solenoids
- Air Cylinders
- Transmission Governor
- Shift Lever Switch
- Over Rule Mech
- Magnet Valve
- Neutral Stop
- Heat Exchanger
- Teleflex Cable and Tubing
- Clutch Linkage
- Clutch Adjustments
- Clutch Pressure Plate
- Clutch Facing

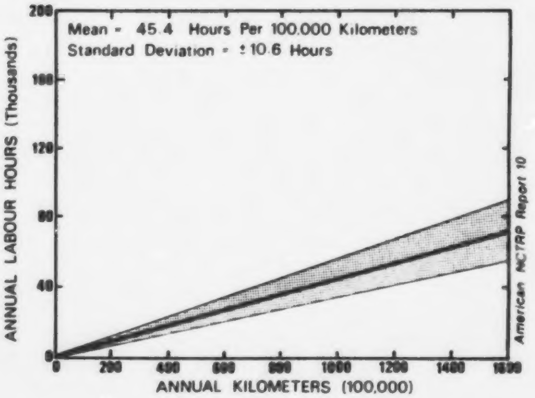
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for SUSPENSION/STEER'G

The suspension and steering system is made up of running repair, removal and replacement, and rebuild activities for all primary components of these systems. Overall, this system is estimated to account for about 4.9 percent of maintenance costs. Labour-hours spent on suspension and steering are about 20 hours per vehicle per year or 4.3 percent of the total. Steering and suspension repair hours are probably related to road conditions (e.g., potholes), although no numerical data were available to evaluate this factor. The annual cost of maintaining the suspension and steering system is about $1,260.

## Compiled Maintenance Measures

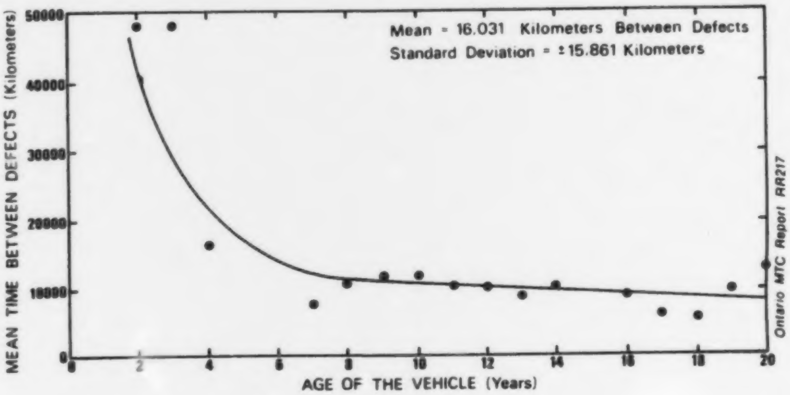
| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 16,031 | n/a | 3,493 |
| MTTR (Hours) | n/a | n/a | n/a | 1.36 |
| Hours/100,000 Kms | 33.6 | n/a | n/a | 38.9 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 17.5 | n/a | n/a | 20.3 |
| Number of Defects | n/a | 3.3 | n/a | 14.9 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $ 442 | $ 810 |
| Parts and Materials | n/a | n/a | $ 391 | $ 450 |
| Total Maintenance Cost | n/a | n/a | $ 833 | $1,260 |

## Components

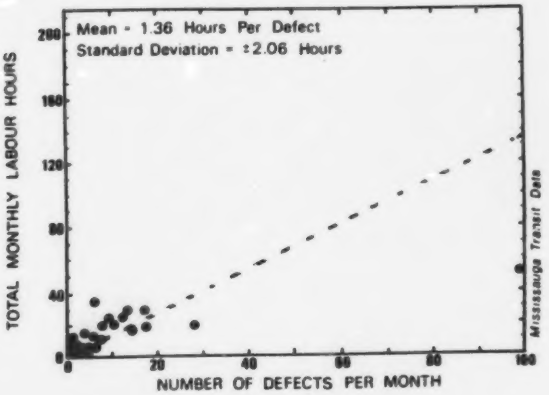
**Suspension and Steering**

- Spindles
- Balance Wheels
- Stub Axles
- Steering Box
- Pitman Arm
- Drag Link
- Tie Rods
- Reducing Box
- Lubrication
- Power Steering
- Steering Wheel
- Bellows and Springs
- Levelling Valve
- Levelling Valve Link
- Radius Rods and Rubbers
- Steering Adjustments
- Lateral Rods and Rubbers
- Air Beam Modifications
- "U" Bolts
- Suspension Support
- Sway Bar and Rubbers
- Spring Shackles
- Steering Shaft

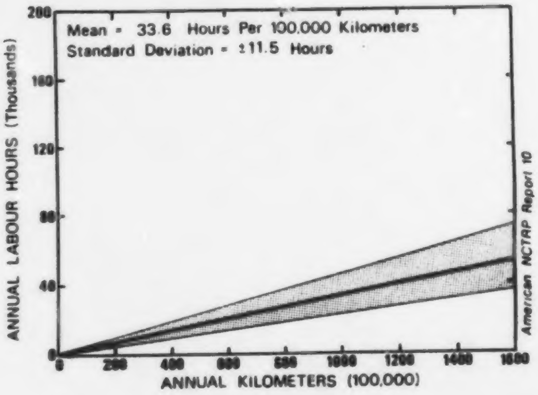
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for WHEELS AND TIRES

Maintenance measures for wheels and tires were difficult to derive. Many transit properties contract for most of their tire work. Variations between properties aere primarily a function of different contracting arrangements. Some of the properties only remove and replace tires, whereas others repair all failures occurring in the night shifts and have the contractor repair those that can wait until the day shift. Wheels and tires are estimated to account for about 3.1 percent of total maintenance labour-hours. This function accounts for about 2.6 percent of the total annual costs and is about $660 per year.

## Compiled Maintenance Measures

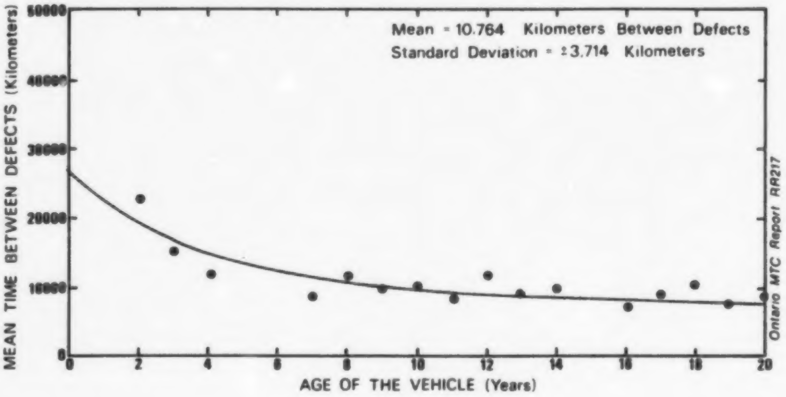
| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 10.764 | n/a | 8.203 |
| MTTR (Hours) | n/a | n/a | n/a | 2.25 |
| Hours/100,000 Kms | 30.2 | n/a | n/a | 27.4 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 15.8 | n/a | n/a | 14.3 |
| Number of Defects | n/a | 4.8 | n/a | 6 4 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | $ 1.296 | $ 570 |
| Parts and Materials | n/a | n/a | $ 0 | $ 90 |
| Total Maintenance Cost | n/a | n/a | $ 1.296 | $ 660 |

## Components

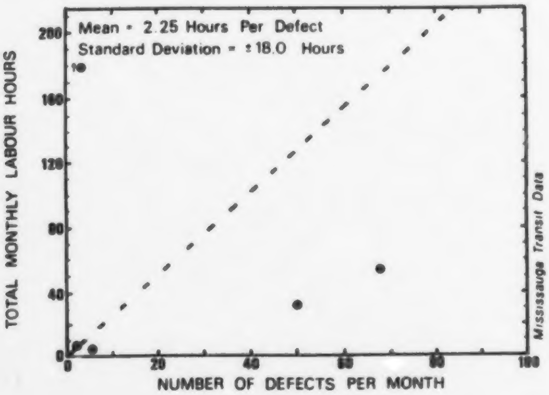
**Tires and Wheels**

- Tire Changes
- Valve Cores
- Regrooving
- Mating
- Broken Wheel
- Loose Wheel
- Wheel Stud
  Axle Shaft Stud
- Broken Hub
- Rims
- Lock Rings

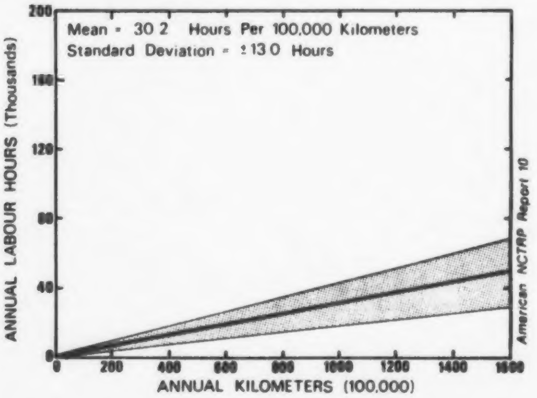
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for COOLING SYSTEM

The cooling function includes all maintenance activities on the vehicle's engine cooling system. Overall, the cooling system accounts for 3.0% of total manpower and is about 14.0 labour-hours per year. The primary cause of deviation between properties is the kilometers of operation, although summer climate probably also has a significant impact. Agencies with moderate summer temperatures most likely have substantially lower man-hour requirements than those with hot summers. Costs for maintaining the cooling system are about $960 per vehicle per year or about 3.8 percent of the total.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 16.636 | n/a | 7.171 |
| MTTR (Hours) | n/a | n/a | n/a | 1.93 |
| Hours/100,000 Kms | 23.0 | n/a | n/a | 26.8 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 12.0 | n/a | n/a | 14.0 |
| Number of Defects | n/a | 3.1 | n/a | 7.3 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | * | $ 560 |
| Parts and Materials | n/a | n/a | * | $ 400 |
| Total Maintenance Cost | n/a | n/a | * | $ 960 |

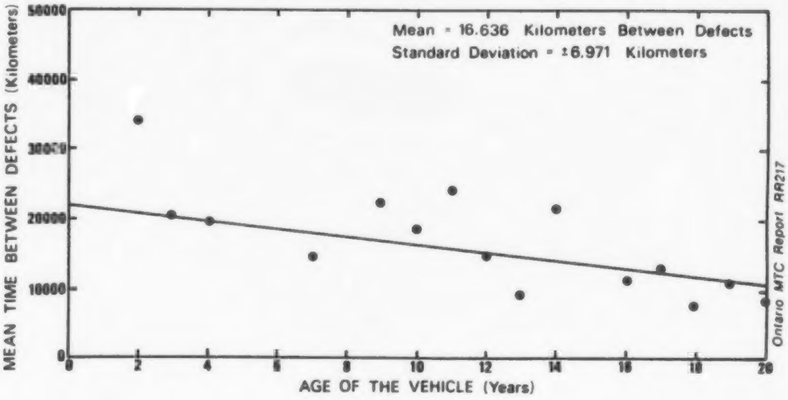
*Included in Engine and Fuel

## Components

**Cooling System**

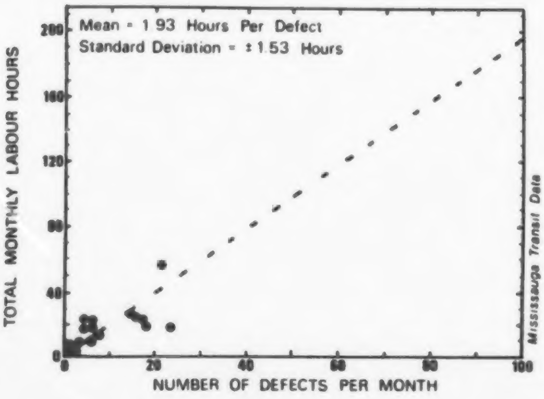
- Shutter Assembly
- Surge Tank
- Hoses
- Hose Clamp
- Alarmstat
- Shutter Thermostat
- Temperature Sending Unit
- Fan Belt
- Fan Drive Assembly
- Hydraulic Fan Assembly
- Fan
- Water Pump
- Shroud
- Radiator
- Leaks
- Block Thermostat
- Vari-Vane
- Vernatherm
- Pressure Relief Valve
- Add Coolant

## Reliability Measure (Mean Time Between Defects)



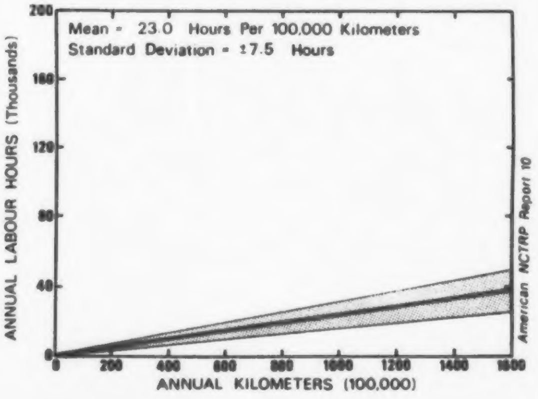
Ontario MTC Report RR217

## Repair Time (Mean Time To Repair)



Mississauga Transit Data

## Manpower Utilization (Labour Hours)



American NCTRP Report 10

# Maintenance Data for HEATING/VENTILATION

The heating and ventilation (and, in some cases, air conditioning) system is made up of running repair, removal and replacement, and rebuild activities on all applicable components. Overall, this system is estimated to account for 3.2 percent of maintenance costs. This is about $820 per vehicle per year. Annual labour-hours are about 9.9 per vehicle which is about 2.1 percent of the total annual labour. The two major factors causing differences between properties is vehicle-kilometers and climate. Much of the remaining deviation that may occur could be attributed to policy.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 14.963 | n/a | 9.416 |
| MTTR (Hours) | n/a | n/a | n/a | 1.78 |
| Hours/100.000 Kms | 16.8 | n/a | n/a | 19.0 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 8.8 | n/a | n/a | 9.9 |
| Number of Defects | n/a | 3.5 | n/a | 5.5 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | * | $ 400 |
| Parts and Materials | n/a | n/a | * | $ 420 |
| Total Maintenance Cost | n/a | n/a | * | $ 820 |

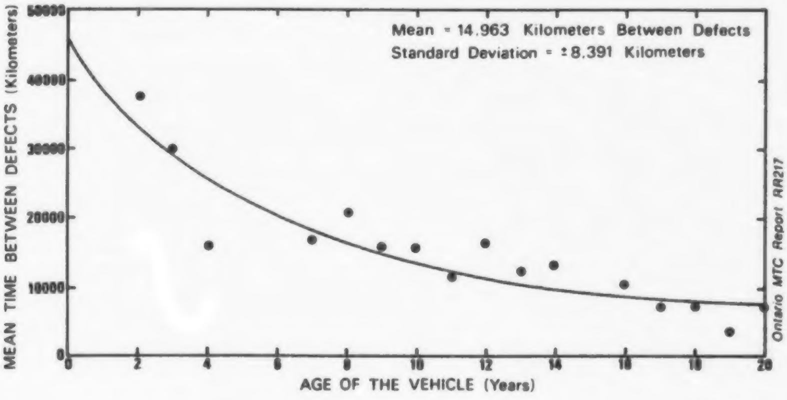
*Included in Engine and Fuel

## Components

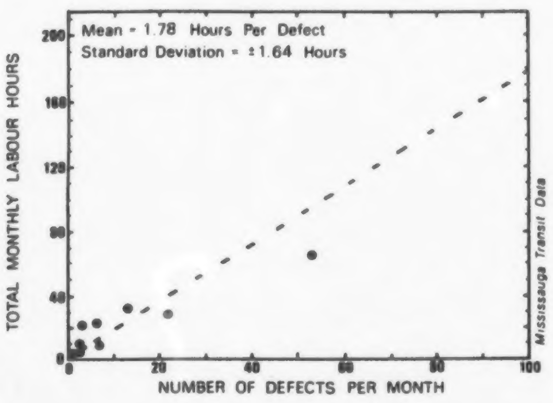
**Heating and Ventilation**

- Air Conditioning
- Circulating Pump
- Gradustat
- Heater Motor/Blower Motor
- Heater Core
- Defroster Motor
- Defroster Core
- Piping for Heating
- Air Lock/Bleed Heaters
- Valve or Air Vents
- Dash Switches/Micro Switches
- Engine Temperature Switch
- Water Valves
- Filters
- Modulating Valve
- Body Thermostats

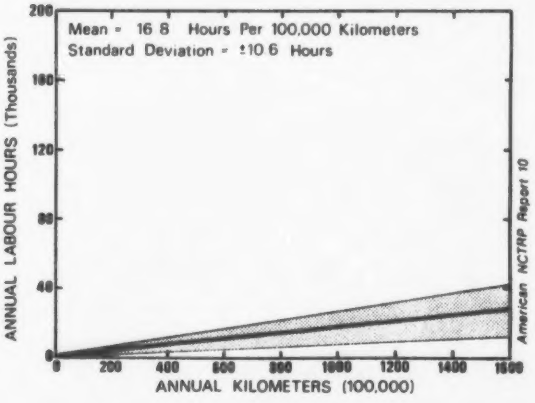
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Maintenance Data for AIR SYSTEM

The air system is made up of running repair, removal and replacement, and rebuild activities for all primary components of this system. Overall, this system is estimated to account for about 3.6 percent of maintenance costs. About 9.5 labour-hours are spent each year on the air system of transit vehicles. This is about 2.0 percent of the total annual labour-hours. The annual costs of maintaining the air system per vehicle are estimated at $920 including parts and materials.

## Compiled Maintenance Measures

| | American Report | Ontario Report | Victoria Data | Miss'auga Data |
|---|---|---|---|---|
| BASIC MEASURES | | | | |
| MTBD (Kilometers) | n/a | 19.993 | n/a | 7.626 |
| MTTR (Hours) | n/a | n/a | n/a | 1.40 |
| Hours/100.000 Kms | 13.9 | n/a | n/a | 18.2 |
| ANNUAL MEASURES | | | | |
| Labour Hours Per Bus | 7.3 | n/a | n/a | 9.5 |
| Number of Defects | n/a | 2.6 | n/a | 6.8 |
| ANNUAL COST | | | | |
| Maintenance Labour | n/a | n/a | * | $ 380 |
| Parts and Materials | n/a | n/a | * | $ 540 |
| Total Maintenance Cost | n/a | n/a | * | $ 920 |

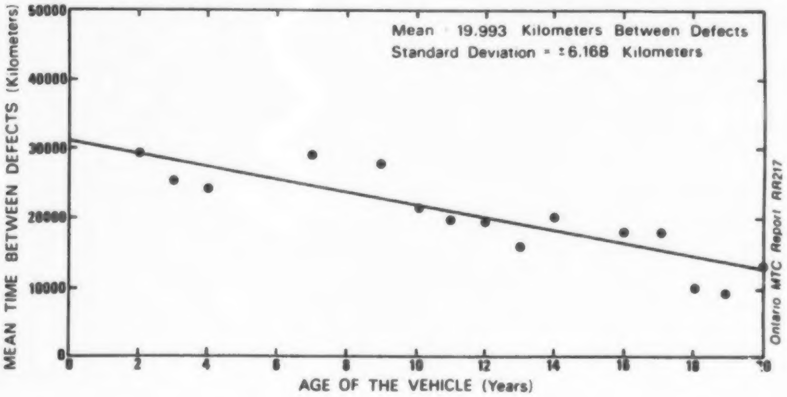
* Included in Braking System

## Components

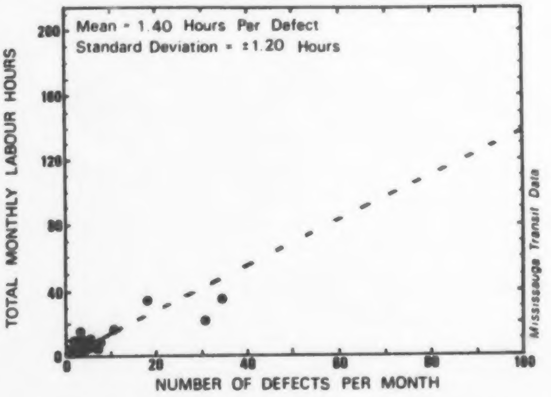
**Air System**

- Compressor
- Air Lines (Main and Brake)
- Air Governor
- Valves
- Expello Valves
- Air Tanks
- Air Bottle
- Alcohol Injector
- Frozen Air Lines
- Safety Valve

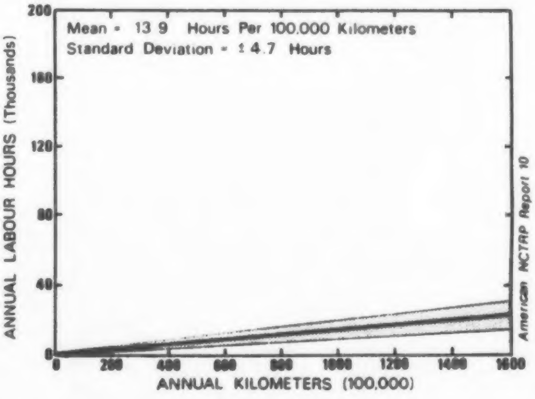
## Reliability Measure (Mean Time Between Defects)



## Repair Time (Mean Time To Repair)



## Manpower Utilization (Labour Hours)



# Appendix B:
# DIAGNOSTIC COST SAVINGS MODEL (DIACSM)

In this appendix, the application of a model to estimate the anticipated savings with vehicle diagnostic systems is described. The model, which is called a Diagnostic Cost Savings Model (DIACSM), was developed in order to assess the following potential impacts of diagnostic systems:

- a decrease in diagnostic labour time;
- an increase in diagnostic/repair accuracy;
- an increase in the failure predictive capability; and
- overall improvement in bus reliability and/or availability.

The difference between maintenance costs in the absence of diagnostic aids and maintenance costs with the application of diagnostic aids is used as the measure of the potential leverage for diagnostic aid systems.

To apply the model, the following representative data was assembled by means of interviews with various transit maintenance managers:

- the relative percentages of maintenance time and/or labour costs spent on diagnostic functions versus repair and installation functions;
- the relative percentages of maintenance time spent by purpose or reason for the maintenance activity, i.e
    - corrective maintenance: unscheduled repairs that are triggered by performance problems and/or failures;
    - preventive maintenance: scheduled planned maintenance (with little or no diagnostics) designed to prevent failures;
    - safety maintenance: regulated safety inspections with specific test and/or inspection requirements.
- the relative accuracy or reliability of repairs by vehicle subsystem.

## DIAGNOSTIC COST SAVINGS MODEL (DIACSM)

The equations that form the basis of the first evaluation model, the diagnostic cost savings model, are shown below:

### Diagnostic Cost Savings Model (DIACSM)

*Exhibit B-1*

$$S = \sum S_{ij} = \sum_{j=1}^{m} \sum_{i=1}^{n} [L_i A_i D_{ij} + P_i A_i (1 - R_i)]$$

$S$ = Total anticipated savings from the application of vehicle diagnostic systems to urban transit vehicles.

$L_i$ = Current annual labour cost for maintenance of subsystem i of an urban transit vehicle.

$P_i$ = Current annual parts cost spent on maintenance of subsystem i of the transit vehicle.

$R_i$ = Current estimated accuracy in diagnosing a fault (i.e., repair accuracy) for subsystem i on the transit vehicle.

$A_i$ = Estimated applicability of a diagnostic system to maintenance of subsystem i of the transit vehicle (taking into account anticipated utilization and potential improvements).

$D_{ij}$ = Current estimated percentage of time spent on diagnosis for purpose j on vehicle subsystem i .

$$D_{ij} = D_i C_{ij}$$

$D_i$ = Current estimated percentage of time spent on testing and diagnostic activities for vehicle subsystem i.

$C_{ij}$ = Current estimated percentage of time for vehicle subsystem i spent on diagnosis for purpose j.

The model assumes that diagnostic systems would be particularly applicable to those facets of the maintenance function in which considerable time is currently spent analyzing or diagnosing maintenance problems and looking for possible solutions. If a function such as servicing/cleaning or body repairs requires little time to analyze problems, the application of a diagnostic system would naturally achieve little benefit. If, on the other hand, however, a function such as the electrical subsystem requires considerable effort to analyze the situation prior to repair activities, the application of a diagnostic system could have a large potential benefit. Another feature of the model is that it determines the potential savings in parts costs by assuming that the accuracy of repair would be increased with diagnostic systems, resulting in a saving in parts costs.

The most serious limitation of this methodology is the lack of good data on the applicability of diagnostic systems to particular subsystems of the transit vehicle. Other data that is based on subjective judgments includes the relative percentages of preventive versus corrective maintenance and the estimated current accuracy in maintenance activities.

## APPLICATION OF THE DIACSM MODEL

The current annual maintenance cost of an urban transit vehicle is provided in Exhibit B-2 -- assuming no diagnostic aid systems. These values were obtained from the detailed analysis of maintenance costs for Mississauga Transit as provided in Appendix A and as summarized in Chapter 5. The current annual maintenance cost of an urban transit vehicle was estimated to be $25,460 of which $18,790 is due to the cost of labour and $6,670 is due to the cost of parts and materials.

**Current Estimated Annual Maintenance Costs by Subsystem**

*Exhibit B-2*

| Vehicle Subsystem | Annual Current Maintenance Costs (Dollars) | | |
|---|---|---|---|
| | Labour ($L_i$) | Parts ($P_i$) | Total ($T_i$) |
| Servicing/Cleaning | $ 4320 | $ 0 | $ 4320 |
| Bus Inspections | 2970 | 100 | 3070 |
| Body Repairs | 2640 | 850 | 3490 |
| Engines and Fuel | 2030 | 380 | 2410 |
| Braking System | 1660 | 1580 | 3240 |
| Electrical System | 1350 | 960 | 2310 |
| Transmission | 1100 | 900 | 2000 |
| Suspension/Steering | 810 | 450 | 1260 |
| Wheels and Tires | 570 | 90 | 660 |
| Cooling System | 560 | 400 | 960 |
| Heating/Ventilation | 400 | 420 | 820 |
| Air System | 380 | 540 | 920 |
| Total Costs | $18790 | $ 6670 | $25460 |

To determine the potential maintenance cost reductions if diagnostic systems were applied, estimates are first required for the current cost of diagnostic and repair activities by reason for the activity (corrective, preventive or safety maintenance). An estimate is also required of the present repair accuracy in order to obtain an indication of the potential benefits that might be achieved from a reduction in parts and materials.

To determine the distribution of time presently spent on maintenance by type and by reason, an estimate of the percentage of time spent on diagnostic or repair activities for each vehicle subsystem was required. Secondly, an estimate of the percentage of time spent on corrective, preventive or safety maintenance was required. These values were obtained from a 'panel of experts'.

The interviewing of a 'panel of experts' was used to develop estimates of relative percentages of time spent by reason of repair, diagnostic versus repair time, and repair accuracy The panel of experts included the maintenance managers and/or supervisors at five transit properties (Hull, Kitchener, London, Mississauga and Victoria). The panel provided fairly consistent estimates for each of the required values and the average of the responses was used in the model.

The estimated percentage of time spent on diagnostic activities (Di) is shown in the first column of Exhibit B-3. Diagnostic activities are highest for bus inspections and maintenance of the electrical systems. Mainten-ance of the engine, transmission, cooling and heating systems also require a fair amount of diagnostic activity at the present time.

The estimated percentage of time spent on corrective, preventive and safety maintenance is also provided in the table (Cij where j = 1, 2, 3). Although all transit properties have some form of preventive maintenance program, most maintenance is corrective since failure is not anticipated. Body repairs are largely an unscheduled corrective maintenance activity whereas bus inspections are usually a scheduled preventive or safety maintenance activity. It is noted that maintenance of the braking system is usually performed for safety or preventive maintenance reasons. The reason for the maintenance activity for many of the other subsystems is judged to be as a result of a failure in about 70 percent of the cases.

Finally, the panel was asked to estimate the current accuracy in diagnosing and correcting faults and the estimated accuracy (Ri) is also shown. It is noted that the transit managers believe that the proper maintenance activity was performed in 90 to 100 percent of the time.

**Distribution of Maintenance Labour by Type and Purpose**

*Exhibit B-3*

| | TYPE | | PURPOSE | | | ACCURACY |
|---|---|---|---|---|---|---|
| Vehicle Subsystem | Test or Diagnostic Labour ($D_i$) | Repair or Install'n Labour ($1-D_i$) | Unscheduled Corrective Maintenance ($C_{i1}$) | Scheduled Preventive Maintenance ($C_{i2}$) | Scheduled Safety Maintenance ($C_{i3}$) | Estimated Repair Accuracy ($R_i$) |
| Servicing/Cleaning | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| Bus Inspections | 1.00 | 0.00 | 0.00 | 0.40 | 0.60 | 1.00 |
| Body Repairs | 0.05 | 0.95 | 0.90 | 0.10 | 0.00 | 0.88 |
| Engines and Fuel | 0.24 | 0.76 | 0.75 | 0.25 | 0.00 | 0.91 |
| Braking System | 0.15 | 0.85 | 0.30 | 0.35 | 0.35 | 0.89 |
| Electrical System | 0.56 | 0.44 | 0.88 | 0.12 | 0.00 | 0.87 |
| Transmission | 0.21 | 0.79 | 0.86 | 0.14 | 0.00 | 0.94 |
| Suspension/Steering | 0.12 | 0.88 | 0.35 | 0.45 | 0.20 | 0.99 |
| Wheels and Tires | 0.13 | 0.87 | 0.65 | 0.25 | 0.10 | 0.97 |
| Cooling System | 0.18 | 0.82 | 0.66 | 0.34 | 0.00 | 0.90 |
| Heating/Ventilation | 0.19 | 0.81 | 0.68 | 0.32 | 0.00 | 0.96 |
| Air System | 0.10 | 0.90 | 0.66 | 0.34 | 0.00 | 0.89 |

Using the estimated values for Di and Cij from Exhibit B-3, a value for Dij (the percentage of diagnostic versus repair time spent on each vehicle subsystem by reason for the activity) can be calculated according to Equation (2) in the model. The estimates for Dij are shown in Exhibit B-4 for the twelve subsystems.

Due to the lack of data, the distribution for each subsystem by type of activity is similar for each of the three purposes. It is also believed that additional accuracy would not necessarily result from a further breakdown.

### Magnitude of Diagnostic Function by Purpose and Subsystem

*Exhibit B-4*

| Vehicle Subsystem | Corrective Maintenance | | Preventive Maintenance | | Safety Maintenance | |
|---|---|---|---|---|---|---|
| | Test or Diagnostic Labour ($D_{i1}$) | Repair or Install'n Labour ($C_{i1}-D_{i1}$) | Test or Diagnostic Labour ($D_{i2}$) | Repair or Install'n Labour ($C_{i2}-D_{i2}$) | Test or Diagnostic Labour ($D_{i3}$) | Repair or Install'n Labour ($C_{i3}-D_{i3}$) |
| Servicing/Cleaning | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| Bus Inspections | 0.00 | 0.00 | 0.40 | 0.00 | 0.60 | 0.60 |
| Body Repairs | 0.05 | 0.86 | 0.01 | 0.10 | 0.00 | 0.00 |
| Engines and Fuel | 0.18 | 0.57 | 0.06 | 0.19 | 0.00 | 0.00 |
| Braking System | 0.05 | 0.26 | 0.05 | 0.30 | 0.05 | 0.35 |
| Electrical System | 0.49 | 0.39 | 0.07 | 0.05 | 0.00 | 0.00 |
| Transmission | 0.18 | 0.68 | 0.03 | 0.11 | 0.00 | 0.00 |
| Suspension/Steering | 0.04 | 0.31 | 0.05 | 0.40 | 0.02 | 0.20 |
| Wheels and Tires | 0.08 | 0.57 | 0.03 | 0.22 | 0.01 | 0.10 |
| Cooling System | 0.12 | 0.54 | 0.06 | 0.28 | 0.00 | 0.00 |
| Heating/Ventilation | 0.13 | 0.55 | 0.06 | 0.26 | 0.00 | 0.00 |
| Air System | 0.07 | 0.59 | 0.03 | 0.31 | 0.00 | 0.00 |

Diagnostic systems will not, of course, have 100 percent applicability -- for some subsystems, it may not be particularly applicable. It also may be under-utilized or not offer any particular improvement. Estimated values for the applicability of a vehicle diagnostic system to each of the twelve subsystems (Ai) is provided in the first column in Exhibit B-5.

Using the estimated values for Ai, Dij, Li, Pi and Ri from the previous tables, the anticipated savings with diagnostic systems can be calculated according to Equation (1) in the model from Exhibit B-1 for each vehicle subsystem. These estimates for Sij -- the anticipated savings -- are shown in Exhibit B-5 for the twelve subsystems. The potential parts and materials savings are shown separately from the potential labour savings. The total cost savings for each subsystem is the sum of the labour savings and the materials savings.

### Estimated Annual Savings with Diagnostic Systems

*Exhibit B-5*

| Vehicle Subsystem | Diagnostic Applica-bility | Labour Savings | | | Parts | Total Cost Savings |
|---|---|---|---|---|---|---|
| | | Corrective Mtce | Preventive Mtce | Safety Mtce | Parts Savings | |
| Servicing/Cleaning | 0.10 | $ 0 | $ 0 | $ 0 | $ 0 | $ 0 |
| Bus Inspections | 0.35 | 0 | 416 | 624 | 0 | 1040 |
| Body Repairs | 0.10 | 12 | 1 | 0 | 9 | 22 |
| Engines and Fuel | 0.85 | 311 | 104 | 0 | 29 | 443 |
| Braking System | 0.75 | 56 | 65 | 65 | 130 | 317 |
| Electrical System | 0.65 | 432 | 59 | 0 | 81 | 573 |
| Transmission | 0.80 | 159 | 26 | 0 | 43 | 228 |
| Suspension/Steering | 0.60 | 20 | 26 | 12 | 3 | 61 |
| Wheels and Tires | 0.60 | 29 | 11 | 4 | 2 | 46 |
| Cooling System | 0.80 | 53 | 27 | 0 | 32 | 113 |
| Heating/Ventilation | 0.70 | 36 | 17 | 0 | 12 | 65 |
| Air System | 0.80 | 20 | 10 | 0 | 48 | 78 |
| Total Cost Savings | | $ 1129 | $ 763 | $ 1548 | $ 388 | $ 2985 |

The total savings if diagnostics could be applied to all subsystems is the sum of Si through i in Exhibit B-5 and is $2,985. This is approximately 12 percent of the total annual cost of maintaining a vehicle; that is, if diagnostics could be applied to all vehicle subsystems, annual maintenance costs could be reduced by 12 percent or almost $3,000 every year.

The annual savings in maintenance costs for each vehicle subsystem is illustrated in Exhibit B-6. The greatest anticipated savings from the application of vehicle diagnostic systems to urban transit vehicles, apart from the benefits for inspections, are in the areas of the electrical, engine, braking, transmission and cooling subsystems. If diagnostics were applied to just these five areas, the potential savings would be $2,714 (assuming that the benefits would pass on to bus inspections). This is over 90 percent of the total anticipated savings. Very little benefits would result from incremental addition of other vehicle subsystems.

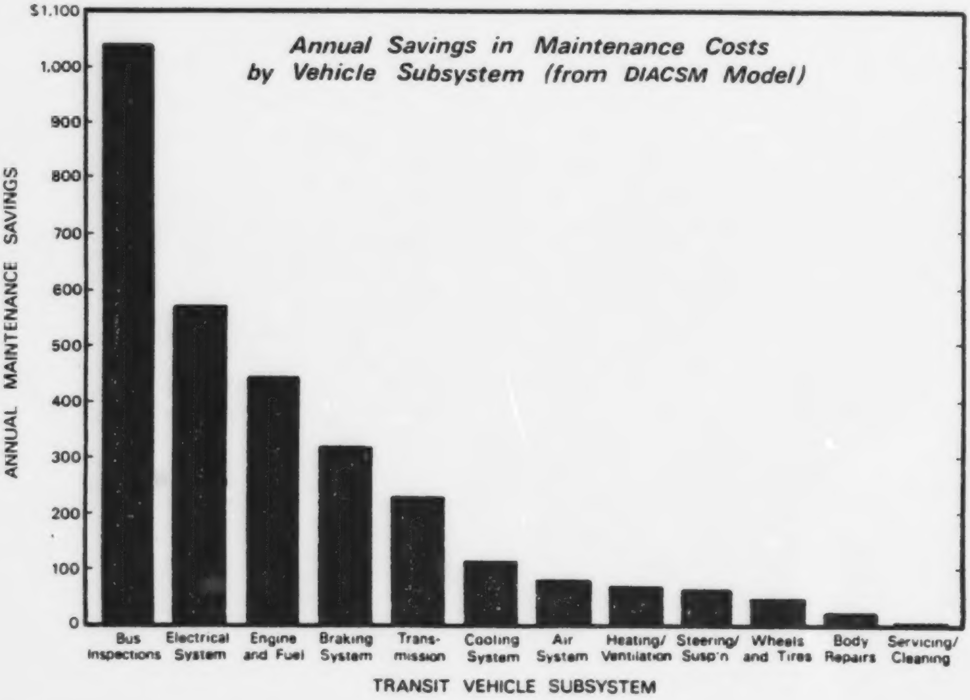

*Annual Savings in Maintenance Costs by Vehicle Subsystem (from DIACSM Model)*

*Exhibit B-6*

The approach adopted here sheds light on the utility of diagnostic aids by transit vehicle subsystem. It provides a means of prioritizing applications according to anticipated savings. It shows that, when considering diagnostic aids, emphasis should be placed on: (1) the electrical subsystem, (2) engines and fuel, (3) the braking subsystem, (4) transmission and (5) cooling system and that considerable benefits would also result in the preventive maintenance inspection function.

Given estimates of current maintenance costs, the current percentage of time spent on testing and diagnostic activities and on corrective versus preventive maintenance, the evaluation process outlined in this chapter using the Diagnostic Cost Savings Model (DIACSM) shows that it is possible to estimate the maximum potential annual savings with diagnostic systems. The potential savings can then be adjusted with a factor to account for the 'applicability' of a diagnostic aid to a particular subsystem to determine the probable annual savings with diagnostics.

The total probable annual savings with an achievable diagnostic system covering the electrical, engine, braking, transmission and cooling subsystems on an urban transit bus was estimated to be $2,714.

# Appendix C:

# MAINTENANCE AND DIAGNOSTICS ANALYSIS MODEL (MADAM)

In this appendix, the applicability and effectiveness of diagnostic systems for urban transit vehicles is discussed within the context of an evaluation methodology that was developed by the Rand Corporation for the Defense Advanced Research Projects Agency in the United States (34). The evaluation methododology is based on two assumptions: first, that current vehicle operating and maintenance practices embody a number of problems that cause maintenance costs to be higher than necessary; and second, that diagnostic systems perform functions that can reduce or eliminate these problems.

Current maintenance problems include: manufacturing faults, improper operation or neglect, maintenance-induced faults, inefficient fault isolation, faulty malfunction diagnosis, late detection of a fault, excessive rework due to improper initial repair and low productivity.

These problems are assumed to be of two basic types: those that increase the frequency of maintenance by decreasing vehicle reliability, and those that increase the cost per maintenance action by decreasing vehicle maintainability.

Frequency of maintenance is influenced by three of the problems: manufacturing faults, improper operation/neglect, and maintenance-induced faults from maintenance actions (the more often maintenance is performed, the greater the possibility that a maintenance-induced fault will result). The maintainability or the resources used in a repair action may be affected by any or all of the following maintenance problems: inefficient fault isolation, faulty malfunction diagnosis, late detection of faults, excessive rework, and low productivity.

The difference between maintenance costs in the absence of diagnosis and costs with all such problems eliminated is a measure of the maxium potential leverage for diagnostic systems. Of course, not all problems will be eliminated completely and the model also takes into account the magnitude of the problems and the diagnostic effectiveness.

The model designed to implement this methodology -- the Maintenance and Diagnostics Analysis Model (MADAM) -- employs a reliability/maintainability approach. Given as inputs the number of kilometers of operation, the reliability/maintainability characteristics of the vehicle subsystems, the problem magnitudes, and diagnostic effectiveness, MADAM estimates vehicle maintenance costs with and without the use of a diagnostic system.

Several analyses illustrate the abilities of the model to identify the most important maintenance problems, examine the effects of changes in problem magnitudes or diagnostic effects, and estimate the potential savings resulting from the use of a particular diagnostic system.

## Impacts of Diagnostic Aid Systems

The effects of diagnostic aid systems on the reliability and maintainability of a vehicle subsystem can be examined within the model. Each of the contributing problems may by ameliorated by the application of one or more diagnostic functions. For example, a fault isolation technique might reduce both inefficient fault isolation and faulty malfunction diagnosis. Diagnostic effects are incorporated within MADAM by decreasing the magnitude(s) of given problem(s) as follows:

$$P_{id} = P_i(1 - F)$$

where Pi and Pid are the magnitudes of a given problem without and with diagnostic functions, and F is the magnitude of the improvement due to the diagnostic functions ($0 < F < 1$).

A value of 1 for F signifies perfect diagnostic effectiveness 100 percent of the time it is applied. More reasonable values for F would, of course, be less than 1, reflecting limited diagnostic applicability. That is, a given diagnostic function may have an impact on a particular problem for only a percentage of the total time the problem occurs and possibly with only limited effectiveness. For example, a diagnostic aid system might perform fault isolation 20 percent better than current procedures. This would therefore cause the magnitude of inefficient fault isolation to be only 80 percent as severe as it was without use of the system.

Parametric estimates of the cost savings attributable to use of diagnostic systems can be obtained by estimating the impacts of diagnostics on the current maintenance problems.

## MAINTENANCE AND DIAGNOSTICS ANALYSIS MODEL (MADAM)

The equations used in the maintenance and diagnostics analysis model from the Rand Corporation study are shown below:

*Exhibit C-1*

### Maintenance and Diagnostics Analysis Model (MADAM)

$$T_a = T_o \prod_i [1 - M_i(1 - D_i)]$$

$T_a$ = Mean time between defects with problem contributions (with or without a diagnostic aid system).

$T_o$ = Mean time between defects without problem contributions (i.e. assuming optimum efficiency and effectiveness).

$M_i$ = Magnitudes of the problems that influence the frequency of unscheduled maintenance actions.

$D_i$ = Magnitudes of diagnostic functions that impact on problems.

$$L_a = L_o / \prod_j [1 - M_j(1 - D_j)]$$

$L_a$ = Mean person-hours per maintenance action with problem contributions (with or without a diagnostic aid system).

$L_o$ = Mean person-hours per maintenance action without problem contributions (i.e. optimum efficiency and effectiveness).

$M_j$ = Magnitudes of the problems that influence the labour requirements of unscheduled maintenance actions.

$D_j$ = Magnitudes of diagnostic functions that impact on problems.

$$P_a = P_o / \prod_k [1 - M_k(1 - D_k)]$$

$P_a$ = Mean parts cost per maintenance action with problem contributions (with or without a diagnostic aid system).

$P_o$ = Mean parts cost per maintenance action without problem contributions (i.e. optimum efficiency and effectiveness).

$M_k$ = Magnitudes of the problems that influence the parts requirements of unscheduled maintenance actions.

$D_k$ = Magnitudes of diagnostic functions that impact on problems.

To determine the frequency of maintenance actions, we first estimate the mean time between defects (To) for each of the subsystems without any problem contributions. To calculate To, the Ta used as input to the model was the mean time between defects from the Mississauga data (i.e., with existing problem contributions). The second step was to estimate the magnitudes of the problems that cause a higher-than-necessary frequency of unscheduled maintenance actions (Mi).

Using the actual values for Ta and the estimated values for Mi, a value for To can be calculated according to the reverse of Equation (1) for each subsystem. Since the calculation is for calibration purposes, the diagnostic function contributions (Di) have been set equal to zero.

Once the values for To, Lo and Po have been calculated in the same manner (i.e. without any problem contributions), they can be used to estimate the values (Ta, La and Pa) for each of the subsystems with problem contributions (with or without diagnostic aids). For example, using the estimated values for To and the Mi, a value for Ta can be calculated according to Equation (1) for each subsystem. Since the following preliminary calculations are for discussion purposes, the diagnostic function contributions (Di) have been set equal to zero initially.

## CALIBRATION OF THE MODEL

### Reliability Input Values

The initial estimates for Ta and M1, M2, and M3 are shown in Exhibit C-2 for each of the twelve subsystems. The method used to assign the Mi values relied heavily on judgment; this procedure was necessitated by the lack of available data on existing problems. The problems were then allowed to impact on Ta using the inverse of the first equation for mean time between defects in Exhibit C-1 and the ideal mean time between defects (To) was calculated by the model. The model aggregates the subsystem values for To to obtain a comparable To for the entire vehicle.

*Exhibit C-2*

**Mean Time Between Defects -- MADAM Inputs**

| Vehicle Subsystem | With Current Problems ($T_a$) | Manufacturing Faults ($M_1$) | Improper Operation/ Neglact ($M_2$) | Maintenance Induced Faults ($M_3$) | Inefficient Fault Isolation ($M_4$) | Faulty Defect Diagnosis ($M_5$) |
|---|---|---|---|---|---|---|
| Servicing/Cleaning | 95 | 0.00 | 0.00 | 0.00 | -- | -- |
| Bus Inspections | 1300 | 0.00 | 0.00 | 0.00 | -- | -- |
| Body Repairs | 1400 | 0.10 | 0.05 | 0.05 | -- | -- |
| Engines and Fuel | 3500 | 0.10 | 0.10 | 0.05 | -- | -- |
| Braking System | 3000 | 0.10 | 0.10 | 0.10 | -- | -- |
| Electrical System | 1500 | 0.15 | 0.15 | 0.10 | -- | -- |
| Transmission | 6200 | 0.10 | 0.10 | 0.05 | -- | -- |
| Suspension/Steering | 3500 | 0.10 | 0.10 | 0.10 | -- | -- |
| Wheels and Tires | 8200 | 0.10 | 0.10 | 0.10 | -- | -- |
| Cooling System | 7200 | 0.10 | 0.10 | 0.10 | -- | -- |
| Heating/Ventilation | 9400 | 0.15 | 0.15 | 0.10 | -- | -- |
| Air System | 7600 | 0.10 | 0.10 | 0.10 | -- | -- |
| Mean Values | 70 | | | | | |

The magnitudes of the problems listed in Exhibit C-2 were derived in a relative way beginning with the engine. The problem magnitudes for all other subsystems were then assigned relative to the engine values.

Considering the engine first, it was thought that improper operation/ neglect (M2) should have a higher magnitude than the other two problems, primarily because the oil system, including the oil filter, is a component of the engine and is often neglected. The low value for maintenance-induced faults (M3) for the engine can be justified by the higher quality of both tools and mechanics required for engine work. It also seems reasonable to assume that the magnitude of manufacturing faults (M1) would be between the magnitudes of the other two problems. For example, an improperly machined oil filter (M1) is not as likely as neglect of oil level (M2), but is probably more likely than forgetting to replace the drain plug after draining and adding new oil (M3).

Since the electrical and heating subsystems have more parts than the other subsystems, it was assumed that they would have a higher possibility of manufacturing faults (M1). They were therefore given a value 50 percent higher (0.15) than the other subsystems. A value of 0.15 for improper operation/neglect (M2) was assigned to the cooling subsystem primarily because of coolant level neglect, which is known to be prevalent. The same value was given to the transmission, braking subsystem and suspension/steering but, in this case, because of improper operating practices, such as riding the brakes, overspeeding, etc.

In the air and and heating subsystems, there is less possibility for either neglect or improper operation and consequently, they were assigned a low value (0.05). Neglect of the battery is the primary reason for assignment of the 0.10 value to the electrical subsystem. With regard to maintenance-induced faults (M3), it was assumed that all subsystems other than the engine and transmission would have higher values. The other subsystems are believed to be more susceptible to maintenance-induced faults. The values listed in the table were used as inputs to the model.

Once the reliability inputs (i.e., frequency of maintenance actions in terms of mean time between defects) are determined, the amount of resources expended during each of these actions is considered. These resources are composed of two contributions, the mean person-hours and the mean parts cost per maintenance action. The ideal person-hours (Lo) and parts costs (Po) were calculated using the reverse of the second and third relationships of the model. The ideal values are increased to the current actual person-hours (La) and parts costs (Pa) for a given maintenance action when the appropriate problem impacts are incorporated (Mj and Mk, respectively).

### Labour Hours Input Values

Exhibit C-3 lists the current mean person-hours for a maintenance action (La), for each of the twelve subsystems. The number of person-hours required to accomplish a maintenance action on the indicated subsystem assuming problem contributions are the values obtained from the Mississauga data (see Appendix A). Also shown are the estimated contributions of the problems (M4 through M8) that, if eliminated, would provide ideal (Lo) values. These values were used as the model inputs.

Mean Person-Hours Per Maintenance Action -- MADAM Inputs

Exhibit C-3

| Vehicle Subsystem | With Current Problems ($L_a$) | Inefficient Fault Isolation ($M_4$) | Faulty Defect Diagnosis ($M_5$) | Late Defect Detection ($M_6$) | Excessive Maintenance Rework ($M_7$) | Low Maintenance Productivity ($M_8$) |
|---|---|---|---|---|---|---|
| Servicing/Cleaning | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bus Inspections | 1.85 | 0.30 | 0.15 | 0.05 | 0.10 | 0.15 |
| Body Repairs | 1.76 | 0.05 | 0.05 | 0.05 | 0.05 | 0.10 |
| Engines and Fuel | 3.40 | 0.40 | 0.10 | 0.30 | 0.10 | 0.10 |
| Braking System | 2.40 | 0.20 | 0.05 | 0.20 | 0.10 | 0.10 |
| Electrical System | 0.95 | 0.50 | 0.20 | 0.05 | 0.15 | 0.10 |
| Transmission | 3.25 | 0.15 | 0.05 | 0.20 | 0.10 | 0.10 |
| Suspension/Steering | 1.36 | 0.20 | 0.05 | 0.20 | 0.10 | 0.10 |
| Wheels and Tires | 2.25 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Cooling System | 1.93 | 0.10 | 0.10 | 0.05 | 0.10 | 0.10 |
| Heating/Ventilation | 1.78 | 0.10 | 0.10 | 0.05 | 0.10 | 0.10 |
| Air System | 1.40 | 0.20 | 0.10 | 0.05 | 0.10 | 0.10 |
| Total Value | 469.00 | | | | | |
| Mean Value | 0.63 | | | | | |

The values for the estimated contributions of the problems (M4 through M8) that would cause a reduction in the La values are determined using the same estimation technique as was used for the Ta values.

The highest value for the engine (0.40) was assigned to inefficient fault isolation (M4). Inefficient fault isolation is simply a measure of the excess time it takes to identify the fault; mechanics, through lack of adequate training or equipment, often take longer than necessary to diagnose problems. The next highest problem magnitude for the engine was 0.30 for late detection of faults (M6). This problem is subject to two considerations: how long a fault can remain undetected and how bad the consequences are as a result of its late detection. In the case of the engine, late detection can be disastrous. For example, a malfunctioning oil pump, if left undetected, could cause permanent engine damage, possibly leading to an engine replacement.

It was thought that the magnitudes of faulty malfunctions diagnosis (M5) (incorrectly diagnosing the malfunction), excessive rework (M7) (redoing the maintenance action), and low productivity (M8) (taking excessive time to accomplish the repair), were rather small (0.10). All other subsystems were assigned problem magnitudes relative to those of the engine.

### Parts Cost Input Values

Exhibit C-4 lists the mean parts cost per maintenance action (Pa) as well as the problem contributions (M9 through M11) that were input to the model to determine the ideal mean parts cost (Po) using the reverse of the third relationship in the model. There are no Mi values for inefficient fault isolation or low productivity since these problems have been assumed to have only a labour implication.

*Exhibit C-4*

Mean Parts Cost Per Maintenance Action -- MADAM Inputs

| Vehicle Subsystem | With Current Problems ($P_a$) | Inefficient Fault Isolation ($M_4$) | Faulty Defect Diagnosis ($M_5$) | Late Defect Detection ($M_6$) | Excessive Maintenance Rework ($M_7$) | Low Maintenance Productivity ($M_8$) |
|---|---|---|---|---|---|---|
| Servicing/Cleaning | 0.0 | -- | 0.00 | 0.00 | 0.00 | -- |
| Bus Inspections | 2.5 | -- | 0.15 | 0.05 | 0.10 | -- |
| Body Repairs | 22.9 | -- | 0.05 | 0.05 | 0.05 | -- |
| Engines and Fuel | 25.6 | -- | 0.10 | 0.30 | 0.10 | -- |
| Braking System | 91.2 | -- | 0.05 | 0.20 | 0.10 | -- |
| Electrical System | 27.7 | -- | 0.20 | 0.05 | 0.15 | -- |
| Transmission | 107.3 | -- | 0.05 | 0.20 | 0.10 | -- |
| Suspension/Steering | 30.3 | -- | 0.05 | 0.20 | 0.10 | -- |
| Wheels and Tires | 14.2 | -- | 0.10 | 0.10 | 0.10 | -- |
| Cooling System | 55.4 | -- | 0.10 | 0.05 | 0.10 | -- |
| Heating/Ventilation | 75.9 | -- | 0.10 | 0.05 | 0.10 | -- |
| Air System | 78.9 | -- | 0.10 | 0.05 | 0.10 | -- |
| Total Value | 6670.0 | | | | | |
| Mean Value | 9.0 | | | | | |

The current mean parts cost (Pa) required per maintenance action on the indicated subsystem assuming problem contributions are the values obtained from the Mississauga data (see appendix). The transmission and engine have the highest mean parts cost per action, since transmission and engine components are often expensive.

The problem contributions (M9 through M11) that were input to the model are also shown in Exhibit C-4. There are no values for inefficient fault isolation or low productivity, since these have been assumed to have only a labour implication. The problem magnitudes for faulty malfunction diagnosis, late detection and excessive rework were assumed to be the same as the values used for the labour inputs to the model.

The ideal mean parts cost (Po) required per maintenance action on the indicated subsystem assuming no problem contributions were then calculated using the model.

## AN ANALYSIS USING THE MODEL

Once the ideal values are calculated (i.e. with no problem contributions), the model can be applied to determine several actual values (i.e. with problem contributions) -- first, the current situation with no diagnostic aids and then, secondly, with diagnostic aids (the model was applied in a spreadsheet format using Lotus 123).

In the ideal situation with no problem contributions, the mean time between defects was calculated for the vehicle as a whole to be 74.4 kilometers. Using the equations in the model with the input values for To and Mi, a value for the mean time between defects of 70.2 kilometers was calculated for the vehicle as a whole with problme contributions. This means that reliability in an ideal situation with no problems is about six percent better than the current situation with its associated problems. The number of maintenance actions would be reduced by 40 per year.

The results of the calculation for the mean time between failures for the two cases, the 'estimated problems' case (i.e, the current situation) and the 'no problems' case (i.e., assuming no diagnostic aids but with all problems set equal to zero), are shown in the first two columns of the table in Exhibit C-5.

Exhibit C-5

**Reliability, Labour and Parts Cost With and Without Problems**

| Vehicle Subsystem | MTBF Without Problems ($T_o$) | MTBF Current Problems ($T_a$) | MTTR Without Problems ($L_o$) | MTTR Current Problems ($L_a$) | Parts Without Problems ($P_o$) | Parts Current Problems ($P_a$) |
|---|---|---|---|---|---|---|
| Servicing/Cleaning | 95 | 95 | 0.20 | 0.20 | 0.00 | 0.00 |
| Bus Inspections | 1300 | 1300 | 0.85 | 1.85 | 1.82 | 2.50 |
| Body Repairs | 1724 | 1400 | 1.29 | 1.76 | 19.62 | 22.88 |
| Engines and Fuel | 4816 | 3500 | 1.04 | 3.40 | 14.50 | 25.58 |
| Braking System | 4357 | 3000 | 1.18 | 2.40 | 62.35 | 91.15 |
| Electrical System | 2179 | 1500 | 0.28 | 0.95 | 17.89 | 27.69 |
| Transmission | 8531 | 6200 | 1.70 | 3.25 | 73.40 | 107.31 |
| Suspension/Steering | 5084 | 3500 | 0.67 | 1.36 | 20.72 | 30.29 |
| Wheels and Tires | 11910 | 8200 | 1.33 | 2.25 | 10.35 | 14.19 |
| Cooling System | 10458 | 7200 | 1.20 | 1.93 | 42.62 | 55.39 |
| Heating/Ventilation | 12934 | 9400 | 1.11 | 1.78 | 58.42 | 75.92 |
| Air System | 9877 | 7600 | 0.78 | 1.40 | 60.73 | 78.92 |
| Mean Values | 74.4 | 70.2 | 0.36 | 0.63 | 4.95 | 9.01 |

The middle two columns of Exhibit C-5 lists the values for Lo obtained from the model when the values specified in Exhibit C-3 for La and M4 through M8 are used as inputs. The results from the MADAM model show that with the estimated problem contributions, a typical maintenance action requires 0.63 person-hours. If all problems are eliminated, this can be reduced to 0.36 hours.

Taking into account the reliability factor which determines the number of maintenance actions per year, the total annual persons-hours to maintain a bus can be reduced from 469.8 to 250.6 hours. Using a value of $40 per hour for the cost of labout, a savings of $8,768 could be realized if all problems could be eliminated.

The final two columns in Exhibit C-5 shows parts costs per maintenance action from the MADAM model when the values of Exhibit C-3 are used as inputs. A value of $9.01 was obtained assuming the problems' impacts. With elimination of these problems, a parts cost of $4.95 results. Taking into account the reliability factor which determines the number of maintenance actions per year, the total parts cost can be reduced from $6,670 to $3,463, a savings of $3,207.

In a manner similar to the preceeding analysis, the total annual maintenance cost for a typical bus with and without problem contributions can be calculated. These results are shown in Exhibit C-6 below. As shown, if the current situation could be improved to the 'ideal' with all maintenance problems eliminated through the application of diagnostic aids, the maximum annual maintenance cost savings would be $11,971 per vehicle. The cost breakdown is as follows:

*Exhibit C-6*

**Maintenance Costs With and Without Problems (Maximum Savings)**

| Vehicle Subsystem | With Current Problems | | | Without Any Problems | | | Maximum Possible Savings |
|---|---|---|---|---|---|---|---|
| | Labour Cost | Parts Cost | Total Cost | Labour Cost | Parts Cost | Total Cost | |
| Servicing/Cleaning | $ 4410 | $ 0 | $ 4410 | $ 4410 | $ 0 | $ 4410 | $ 0 |
| Bus Inspections | 2960 | 100 | 3060 | 1280 | 73 | 1353 | 1707 |
| Body Repairs | 2615 | 850 | 3465 | 1557 | 592 | 2149 | 1316 |
| Engines and Fuel | 2021 | 380 | 2401 | 450 | 157 | 606 | 1794 |
| Braking System | 1664 | 1580 | 3244 | 564 | 744 | 1308 | 1936 |
| Electrical System | 1317 | 960 | 2277 | 264 | 427 | 691 | 1587 |
| Transmission | 1090 | 900 | 1990 | 415 | 447 | 862 | 1128 |
| Suspension/Steering | 808 | 450 | 1258 | 274 | 212 | 486 | 772 |
| Wheels and Tires | 571 | 90 | 661 | 232 | 45 | 277 | 384 |
| Cooling System | 557 | 400 | 957 | 239 | 212 | 451 | 506 |
| Heating/Ventilation | 394 | 420 | 814 | 178 | 235 | 413 | 401 |
| Air System | 383 | 540 | 923 | 163 | 320 | 483 | 440 |
| Total Values | $18790 | $ 6670 | $25460 | $10026 | $ 3463 | $13489 | $11971 |

The greatest savings can potentially be achieved in the braking, engine and electrical subsystems. Vehicle inspections also offer good potential for diagnostic aids. There appears to be little benefit in applying diagnostics to the air system, heating or cooling system, to wheels and tires or to body repairs.

**Diagnostic Impacts**

The preceding table provided the maximum potential cost savings assuming that diagnostic systems would eliminate all problems completely. Naturally, this would not occur. Diagnostic systems would, in fact, have only limited applicability in eliminating the problems.

Based on the analysis by the Rand Corporation for the United States Army, it was assumed that the diagnostic improvement function would be somewhere between 0.10 and 0.30, depending on the vehicle subsystem and the function of the diagnostic aid. The assumed values for Di are provided in Exhibit C-7 on the following page.

The magnitude of the diagnostic function was assumed to be 25 percent for the engine system; 24 percent for the transmission; 22 percent for vehicle inspections; 20 percent for the cooling system; 18 percent for the air system; 17 percent for heating/ventilation; 13 percent for the braking system; 12 percent for both the electrical and wheels/tires systems; 10 percent for the suspension/steering system; and 2 percent for the body.

Exhibit C-7

### Assumed Diagnostic Improvement Functions

| Vehicle Subsystem | Manufacturing Faults ($D_1$) | Improper Operation/ Neglect ($D_2$) | Maintenance Induced Faults ($D_3$) | Inefficient Fault Isolation ($D_4$) | Faulty Defect Diagnosis ($D_5$) | Late Defect Detection ($D_6$) | Excessive Maintenance Rework ($D_7$) | Low Maintenance Productivity ($D_8$) |
|---|---|---|---|---|---|---|---|---|
| Servicing/Cleaning | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Bus Inspections | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 | 0.22 |
| Body Repairs | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Engines and Fuel | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| Braking System | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 | 0.13 |
| Electrical System | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Transmission | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 | 0.24 |
| Suspension/Steering | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Wheels and Tires | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 |
| Cooling System | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Heating/Ventilation | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 |
| Air System | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 | 0.18 |

Incorporating these broad assumptions on the applicability of diagnostic aids to subsystems, the total annual maintenance costs for a typical bus with and without diagnostic aids were calculated. These results are shown in Exhibit C-8 and illustrated in Exhibit C-9. Using the estimated problem magnitudes and the estimated contribution of diagnostic systems in solving these problems, the potential maximum savings would be $3,088 per vehicle annually. The cost breakdown is as follows.

Exhibit C-8

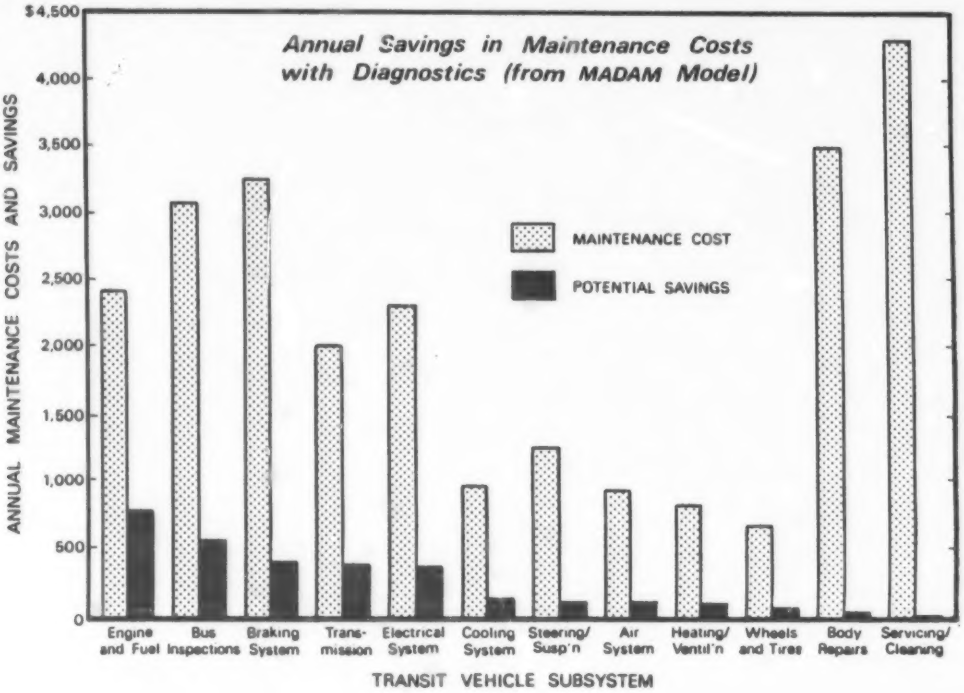
### Maintenance Costs With and Without Diagnostics (Probable Savings)

| Vehicle Subsystem | With Diagnostic Aids | | | With Diagnostic Aids | | | Probable Diagnostic Savings |
|---|---|---|---|---|---|---|---|
| | Labour Cost | Parts Cost | Total Cost | Labour Cost | Parts Cost | Total Cost | |
| Servicing/Cleaning | $ 4410 | $ 0 | $ 4410 | $ 4410 | $ 0 | $ 4410 | $ 0 |
| Bus Inspections | 2960 | 100 | 3060 | 2419 | 93 | 2512 | 548 |
| Body Repairs | 2615 | 850 | 3465 | 2587 | 844 | 3431 | 34 |
| Engines and Fuel | 2021 | 380 | 2401 | 1325 | 299 | 1624 | 776 |
| Braking System | 1664 | 1580 | 3244 | 1431 | 1423 | 2854 | 390 |
| Electrical System | 1317 | 960 | 2277 | 1046 | 865 | 1911 | 366 |
| Transmission | 1090 | 900 | 1990 | 853 | 754 | 1607 | 384 |
| Suspension/Steering | 808 | 450 | 1258 | 720 | 415 | 1135 | 124 |
| Wheels and Tires | 571 | 90 | 661 | 509 | 83 | 592 | 69 |
| Cooling System | 557 | 400 | 957 | 467 | 350 | 817 | 140 |
| Heating/Ventilation | 394 | 420 | 814 | 342 | 379 | 721 | 93 |
| Air System | 383 | 540 | 923 | 326 | 490 | 815 | 108 |
| Total Values | $18790 | $ 6670 | $25460 | $16435 | $ 5993 | $22428 | $ 3032 |

The largest probable savings would result in applying diagnostics to the engine and fuel system, the braking and transmission systems, and the electrical and cooling systems. If a comprehensive diagnostic system could be developed and applied to these systems, as well as to the vehicle testing and inspection function, an estimated annual savings of $2,604 would result for each vehicle.

If such a comprehensive diagnostic system could be developed to cover all the aforementioned vehicle subsystems, about 85 percent of the total annual potential savings could be achieved. If only the engine, transmission and inspection systems are considered, the annual savings would be about $1,700 (about 60 percent of the potential).

*Exhibit C-9*



***Annual Savings in Maintenance Costs with Diagnostics (from MADAM Model)***

## SENSITIVITY ANALYSIS

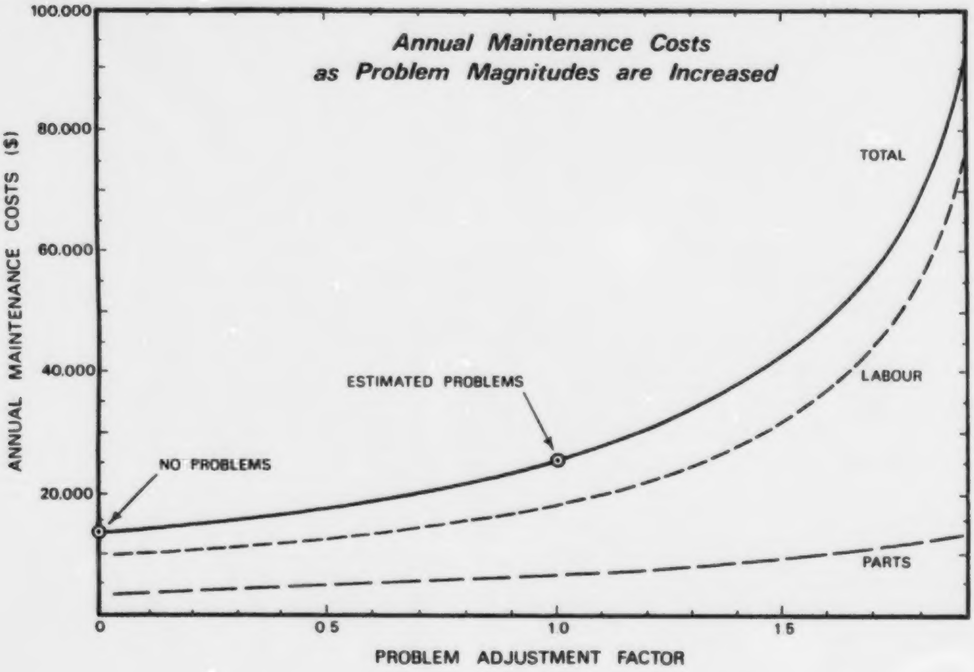
The maintenance and diagnostic analysis model (MADAM) offers a tool for several possible areas of investigation in the field of vehicle maintenance costs. At this point in the study, two areas of sensitivity have been addressed: magnitude of the problems and effectiveness of diagnostics in reducing the problems.

### Magnitude - Problems

The first sensitivity analysis was an examination of the estimated problem magnitudes. If they were higher than originally estimated, maintenance costs would be driven up. A given problem magnitude, however, could not simply be arbitrarily increased, since there would be no basis for doing so. In addition, the quality of the available data is such that examination of numerous cases is not justified. Since it was felt that the relative magnitudes of the problems were essentially correct, all problem magnitudes were increased proportionately.

Therefore, for this sensitivity analysis, the model was ran a number of times: each time with a factor (from 0.0 to 1.9) applied to either increase or decrease the mganitude of the assumed problems.

The results of this analysis on the sensitivity of the results to the magnitude of the current maintenance problems are shown in Exhibit C-10. The first and second highlighted points are the 'no problems' case and the 'estimated problems' case respectively. Although the annual total cost per vehicle increases fairly slowly up to approximately the base or 'estimated problems' case level, after this point there is almost an exponentially increasing dependence.



***Annual Maintenance Costs as Problem Magnitudes are Increased***

*Exhibit C-10*

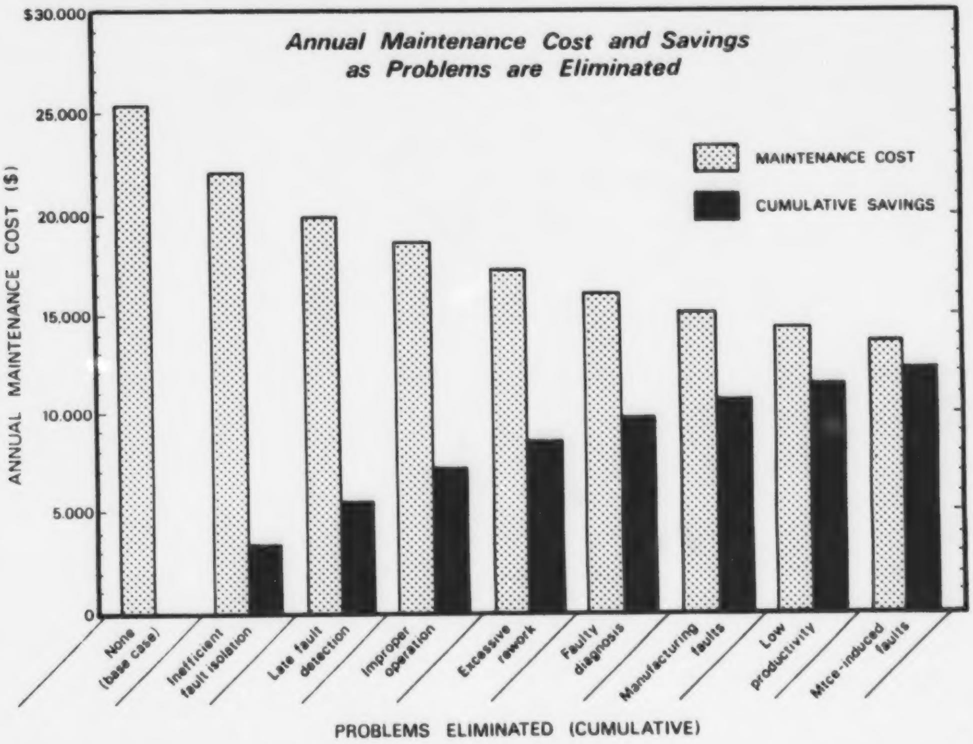
A sensitivity analysis of this type is useful in that it provides more insight into the effect of the problem contributions on the annual costs of maintenance. It indicates that although the problem magnitudes assigned in this study may not be exact, they are probably within reasonable range of the correct values.

## Effectiveness - Problems

The second area was to identify those problems that would provide the most leverage in reducing maintenance costs, if they could be eliminated. The approach developed to answer this question is as follows: Successive model results were obtained with each of the problems independently assigned a magnitude of zero, while the magnitudes of all other problems were held constant at the values specified. The results provided a basis for ranking of the importance of the various problems and provides an indication of the most opportune diagnostic functions.

MADAM was then run several times, each time successively removing the problem that would have the most leverage in reducing maintenance costs. The results provided the basis for a ranking of the problems' capability to reduce total maintenance cost through their elimination. A bar chart illustrating the results of this process is shown in Exhibit C-11.

*Exhibit C-11*



With all the contributing problems present (the base case), the total maintenance cost per vehicle is $25,460 annually, while with all problems eliminated this cost is reduced by 47 percent, to $13,489. The elimination of inefficient fault isolation alone provides a 13 percent decrease from the base case. Almost half the savings in going from the base case to the 'no problem' case (22 percent out of a possible 47 percent) can be achieved by eliminating only two of the problems -- inefficient fault isolation and late detection of faults.

A sensitivity analysis of this type can provide useful guidance as to which function(s) a proposed diagnostic system should perform for maximum benefit. It could also provide the basis for comparison of two proposed systems capable of performing different diagnostic functions. From the preceeding analysis, a diagnostic system that would improve the efficiency and timeliness of fault isolation would be most effective. A diagnostic system to increase productivity would have low effectiveness.

## Final Comment

Although the model used in this analysis is not perfect, the approach adopted sheds light on both the utility of diagnostic aids by function and vehicle component and the estimation of maintenance costs.

Given estimates of current maintenance costs, the operating and maintenance 'problems' that presently exist, and their magnitudes, it is possible to estimate the potential leverage of diagnostic systems. Potential leverage is the difference between current maintenance costs (which include contributions by existing problems) and maintenance costs if all problems could be eliminated.

Obviously, diagnostic systems cannot eliminate all the problems; estimates of their actual impacts are therefore necessary. These estimates are in terms of the extent to which the various problems could be ameliorated. Using fairly conservative estimates of diagnostic impacts, an estimate of the potential annual savings from diagnostic aids were calculated. These estimates provide a basis for prioritizing the implementation of diagnostic systems by function and vehicle component, as well as a means of determining the benefits to be achieved for input into a cost-effectiveness evaluation of candidate diagnostic systems.

# Appendix D:
# SOME DIAGNOSTIC EQUIPMENT SUPPLIERS

## ALARM/SHUTDOWN SYSTEMS

**Air Refiner**
P.O. Box 95209
Oklahoma City, Okl. 73143
405-672-2311

Perry Low Coolant Indicator automatically shuts down engine.

**Armburst-Matthews Corp.**
4452 W. 16th St.
Chicago, Ill. 60623
312-762-8150

Levelstat Models monitor cooling system temperature and oil pressure. System has alarm and shutdown capabilities.

**Beam Products Mfg. Co.**
3040 Rosslyn St.
Los Angeles, Calif. 90065
818-247-7050

Safety switch shuts off liquid petroleum gas when oil pressure is absent. Used on forklifts and other LPG-powered vehicles.

**Con-Serv. Inc.**
3801 Dahlman Ave.
Omaha, Neb. 68107
402-331-3540

Warning device notifies driver that engine has been idling more than three minutes. Engine shutdown occurs after four minutes.

**Flight Systems**
P.O. Box 25
Mechanicsburg, PA 17055
717-697-0333

Model 995 Diesel Monitor monitors a combination of coolant pressure and temperature. Monitors oil pressure at specific engine RPMs. Has audible alarm and shutdown, plus status panel to identify problem. Expandable to many multi-functions.

**Freightliner Corp.**
4747 N. Channel Ave.
Portland Ore. 97217
503-283-7735

Vigil II is multi-alarm and shutdown system, available on FL 112 Class 8 conventional tractor. Microprocessor, through programming of parameters, monitors oil pressure, water level, and water temperature. When parameter levels are exceeded, shutdown occurs after 30-second delay to allow movement to safety.

**Hewitt Industries of Los Angeles**
129 Sheldon St.
El Segundo, Calif. 90245
213-772-1883

Mulit Alarm II monitors oil pressure, coolant level and temperature, and air pressure. System shuts down engine if customer requires this feature.

**Isspro, Inc.**
315 S.E. 7th Ave.
Portland, Ore 97214

Engine Shutdown Delay model, Issprolarm Water Check and Turbo Temperature Monitor can be used in conjunction with each other to monitor engine operation. System expandable to eight wire functions

**Kysor/Cadillac**
Division of Kysor Industrial Corp.
1100 Wright St.
Cadillac, Mich. 49601
616-775-4681

Alarmstat and Pressurestat models and combinations of these models.

Systems monitor coolant level, oil pressure and can display warning lights, audible alarms and provide engine shutdown if the customer desires this feature.

**Nartron Corp.**
5000 No. U.S. 131
Reed City, Mich. 49677
616-832-5525

Bark II is solid state audio alarm system which can monitor low brake fluid, low oil pressure, and high engine temperature.

Voltron is an electrical malfunction alarm system that senses battery condition, and warns driver when voltage goes above or below preset limits.

**Paine Instruments, Inc.**
2401 Bayview Street
Seattle, Wash. 98144
206-723-1705

Manufacturers only for the military. Wateralarm includes low level and aeration detectors for cooling systems.

**Racor Division**
Parker Hannifin Corp.
P.O. Box 3208
Modesto, Calif. 95353
209-521-7860

Sentinel Diesel Protection Systems Non-electronic mechanical systems that monitor oil pressure and coolant temperature.

**Robertshaw Controls Co.**
Tennessee Division
P.O. Box 400
Knoxville, Tenn. 37901
615-546-0550

Mini-Tex Liquid Level Detector. Additional information can be obtained from the manufacturer.

**Sterling Technologies, Inc.**
21211 Bridge Street
Southfield, Michigan 48034
313-353-4090

Multi-function systems monitor coolant and oil levels, RPMs, engine temperature, and can include other parameters.

**Sturdy Controls Division**
1822 Carolina Beach Road
Wilmington, N.C. 28401
919-763-8261

Engine shutdown system incorporates speed controls.

**Synchro-Start Products, Inc.**
8109 N. Lawndale Street
P.O. Box 147
Skokie, Illinois 60076
312-673-7730

EPS Engine Protection System monitors oil pressure, coolant temperature, oil level.

**Ulanet Watchdog Systems**
413-15 Market Street
Newark, New Jersey 07105
201-589-4876

Watchdog System offers systems for gasoline and diesel engines. The Olt model features a three-indicator/sensor module. The system monitors oil pressure, rapid change in level or pressure, and coolant temperature. Available as alarm or shutdown system.

**Webb Enterprises, Inc.**
320 8th Street West
West Fargo, N.D. 58078
701-281-0002

Coolant Monitor and Oil Monitor offered as separate alarm systems

**Westberg Manufacturing, Inc.**
3400 Westach Way
Sonoma, California 95476
707-938-2121

PLW/THW are solid state devices that monitor engine temperature and oil pressure. Monitor must be used in conjunction with Westach gauges. Alarms can be connected to shutdown functions.

## DIAGNOSTIC SYSTEMS

**Detroit Diesel Allison**
Division of General Motors Corp.
13400 Outer Drive, West
Detroit, Michigan 48239-4001
313-556-5800

Detroit Diesel Electronic Control (DDEC) is an integral microprocessor-based, electronic engine control and fuel injection system which can include a self-diagnostic system that monitors all engine sensors and electronic components and recognizes system faults. Diagnostic codes are logged into the Electronic Control Module (ECM) memory and can be read by a mechanic using an inexpensive diagostic reader to identify the problem.

Allison Transmission Electronic Control (ATEC) consists of an electronic control unit, throttle sensor, speed sensor, push button shift sensor, electro-hydraulic valve body and a 'check transmission' driver warning light. To enhance troubleshooting, a diagnostic analyzer is available.

**Cummins Engine Company Inc.**
Service Products Company Div.
Mail Code 80201, Box 3005
Columbus, Indiana 47202-3005
812-377-8233

The Cummins' Compuchek diagnostic system includes computer equipment console and hand-held keyboard along with 13 different electronic sensors attached to the engine with quick-connect fittings. Free acceleration and deceleration from low idle to high idle and engine cranking provide diagnostic data required to produce computerized diagnostic report.

**TRW Controls & Fasteners Group**
Transportation Electronics Division
24175 Research Drive
Farmington Hills, Michigan 48024
313-478-7210

TRW's ETEC II (Electronic Engine Control System) for Cummins engines detects engine rpm and vehicle speed and controls fuel flow to the engine. A diagnostic unit is available for system check-out and troubleshooting.

**Sun Electric Corporation**
One Sun Parkway
Crystal Lake, Illinois 60014
815-459-7700

The Sun Interrogator is a microprocessor-based engine analyzer designed for the testing and diagnosis of gasoline engines.

**General Electric Company**
Knowledge-Based Systems Program
Research and Development Center
P.O. Box 43
Schnectady, N.Y. 12345
Dr. Francis S. Lynch, Manager
518-385-4171

General Electric's Diesel-Electric Locomotive Troubleshooting Aid

(DELTA) is being used in railroad 'running repair shops' to assist maintenance personnel in isolating and repairing a large variety of diesel-electric locomotive faults. It uses an expert system to isolate problems.

**Fleet-Trak Systems Inc.**
130 Slater Street, Suite 1025
Ottawa, Ontario K1P 6E2
613-563-1603

The Fleet-Trak vehicle location monitoring system using Loran C can also include on-board engine monitoring and data storage -- monitoring speed, rpm, oil temperature, fuel flow, coolant temperature, etc.

**United Technologies**
Hamilton Test Systems
2202 North Forbes Blvd.
Tucson, Arizona 85745
602-620-4063
Wayne M. Burns, Program Mgr

United Technologies Automatic Bus Diagnostic System (ABDS) is a computerized tool for fault identification and isolation in diesel-powered buses and their subsystems.

ABDS consists of a Fuel Island Unit and a Maintenance Area Unit which respectively perform a daily checkout and a comprehensive diagnostic test.

## MONITORING SYSTEMS

**General Railway Signal**
Bus Management and
Communications Systems
P.O. Box 600
Rochester, New York 14692
716-436-2020

GRS' Fleet Management System's Vehicle Logic Unit provides radio control, vehicle location and sensor data acquisition with optional passenger counting, farebox data interface and destination sign control.

The system is in place in San Antonio and Los Angeles.

**Motorola Communications and Electronics Inc.**
1301 East Algonquin Road
Schaumburg, Illinois 60196
312-397-1000

Motorola's Metrocom III is an on-board control head for transit buses that facilitates voice and data communications, including vehicle location monitoring. Up to 6 mechanical alarms can be attached (hot engine, low oil or air pressure, farebox tampering, etc.). Systems are in place in Westchester, N.Y. and New Jersey Transit.

**II Morrow Incorporated**
P.O. Box 13549
Salem, Oregon 97309
503-581-8101

II Morrow's Vehicle Tracking System (VTS) uses a Loran C receiver on-board the vehicle to monitor vehicle locations. Used on transit system in Champaign, Illinois.

**AVM Systems Inc.**
5050 Mark IV Parkway
Fort Worth, Texas 76101
817-625-2811
Maurice H. Lanman

Automatic vehicle monitoring systems and associated hardware.

**ITT SEL Canada**
ITT Industries of Canada Ltd.
5075 Yonge Street, 8th Floor
Toronto, Ontario M2N 6C6
416-223-8611

Automatic train control, bus monitoring systems, computer aided dispatch.

**Messerschmitt-Boelkow-Blohm**
Advanced Transport Systems Dept.
P.O. Box 80 12 65
D-8000 Munich 80, West Germany
49-89-6000 3419
Peter C. Bittner

Automated vehicle control and monitoring systems and automated information systems.

## LOCATION SYSTEMS

**ETAK Incorporated**
1455 Adams Drive
Menlo Park, California 94025
415-328-3825
Jon B. Korchin, Sales Manager

ETAK's Navigator shows a moving vehicle's location on a video map by using an 'augmented dead reckoning' scheme that compares the vehicle's movements with stored map data.

## ELECTRONIC DATA RECORDERS

**Stemco-Engler**
250 Culver Avenue
Jersey City, New Jersey 07305
201-332-5353

Stemco-Engler's Vehicle Management System (VMS) on-board trip recorder records average mileage, road speeds, engine speeds, elapsed time and idle time.

**Cadec Systems**
Londonderry, New Hampshire
800-CADEC20

The CADEC 300 on-board memory module records data from driver plus data from sensors monitoring road speed, engine rpm, mileage and the time of day.

# Appendix E:
# SAE J1708 RECOMMENDED PRACTICE

In this appendix, the SAE Recommended Practice for "Serial Data Communications Between Microcomputer Systems in Heavy Duty Vehicle Applications -- SAE J1708 Jan86" is provided courtesy of the Society of Automotive Engineers, Inc. This Recommended Practice is reproduced from the "1987 SAE Handbook, Volume 4: On-Highway Vehicles and Off-Highway Machinery". This and other volumes of the Handbook may be ordered by contacting Customer Service, SAE, 400 Commonwealth Drive, Warrendale, PA. 15096 (412) 776-4970.

## SERIAL DATA COMMUNICATIONS BETWEEN MICROCOMPUTER SYSTEMS IN HEAVY DUTY VEHICLE APPLICATIONS—SAE J1708 JAN86

**SAE Recommended Practice**

Report of the Truck and Bus Electrical Committee approved January 1986.

*1. Forward*—This SAE Recommended Practice has been developed by the Truck and Bus Electronic Interface Subcommittee of the Truck and Bus Electrical Committee. The objectives of the subcommittee are to develop information reports, recommended practices, and standards concerned with the interface requirements and connecting devices required in the transmission of electronic signals and information among truck and bus components.

**1.1 Objectives**—Some of the goals of the subcommittee in developing this recommended practice were to:

—minimize hardware cost and overhead;

—provide flexibility for expansion and technology advancements with minimum hardware and software impact on inplace assemblies;

—utilize widely accepted electronics industry standard hardware and protocol to give designers flexibility in parts selection;

—provide a high degree of electromagnetic compatibility;

—provide original equipment manufacturers, suppliers, and aftermarket suppliers the flexibility to customize for product individuality and for proprietary considerations.

*2. Purpose*—The purpose of this recommended practice is to define a general-purpose serial data communication link that may be utilized in heavy-duty vehicle applications. It is intended to serve as a guide toward standard practice to promote serial communication compatibility among microcomputer-based modules. The primary use of the general-purpose communications link is expected to be the sharing of data among stand-alone modules to cost-effectively enhance their operation. Communication links used to implement functions that require a dedicated communication link between specific modules may deviate from this recommended practice.

*3. Scope*—This document defines a recommended practice for implementing a bi-directional, serial communication link among modules containing microcomputers. This document defines those parameters of the serial link which relate primarily to hardware and basic software compatibility such as interface requirements, system protocol, and message format. The actual data to be transmitted by particular modules, which is an important aspect of communications compatibility, is not specified in this recommended practice. These and other details of communication link implementation and use should be specified in the separate application documents referenced in Section 3.1.

**3.1 Related Documents**

3.1.1 Electronics Industries Association Standard RS-485 (EIA RS-485) "Standard for Electrical Characteristics of Generators and Receivers for Use in Balanced Digital Multipoint Systems," April 1983.

3.1.2 SAE J1455, Recommended Environmental Practices for Electronic Equipment Design (Heavy-Duty Trucks).

3.1.3 It is recommended that a separate applications document be published by the manufacturer for each device using the serial link. These documents should define the data format, message I.D.'s, message priorities, error detection (and correction), maximum message length, percent bus utilization, and methods of physically adding/removing units to/from the line for the particular application.

**3.2 Glossary**

3.2.1 ACCESS TIME—Two bit times multiplied by the message priority (which ranges from 1 to 8) added to the Idle Line time.

3.2.2 BAUD—The maximum number of analog signal transitions per second that can occur on a channel. In this coding system, this is the reciprocal of the bit time.

3.2.3 BIT TIME—Duration or period of one unit of information.

3.2.4 CHARACTER TIME—The duration of one character. The character must start with a low logic bit, then eight bits of data (least significant bit first) followed by a high logic level stop bit.

3.2.5 CONTENTION—A state of the bus in which two or more transmitters are turned on simultaneously to conflicting logic states.

3.2.6 DIFFERENTIAL SIGNAL—A two-wire process in which both lines are switches as opposed to a single-ended signal wherein one line is grounded and the signal line is switched between logic states.

3.2.7 IDLE STATE—The state which produces a high logic level on the input of the bus receiver when all transmitters on the network are turned off.

3.2.8 IDLE LINE—The condition which exists when the bus has remained in a continuous high logic state for at least ten bit times after the end of the last Stop Bit.

Note: The Idle Line serves as the delimiter between messages on the bus. A receiver which cannot distinguish between a Stop Bit and any other high logic state may become synchronized with the bus by noting the receipt of 12 consecutive high logic bits. In the absence of errors, the first low logic bit (0) following 12 consecutive high logic bits (1) is the Start Bit of a Message Identification Character (that is, the first character of a message).

3.2.9 MESSAGE PRIORITY—A measure of message criticality assigned on a scale of 1–8 by the appropriate applications document. The most critical message has a priority of one.

3.2.10 NODE—A receiver or transceiver circuit connected to the bus.

3.2.11 START BIT—Initial element of a character defined as a low logic level of one bit time duration as viewed at the output of the bus receiver.

3.2.12 STOP BIT—Final element of a character defined as a high logic level of one bit time duration as viewed at the output of the bus receiver.

*4. Electrical Parameters*—The electrical parameters of this serial data link are a modification of the EIA RS-485 standard. In some areas this document conflicts with RS-485. This recommended practice shall serve as the guiding document in such cases. Appendix A details a serial data bus standard node which defines the interface circuit parameters. Operation of this standard node is detailed in this section.

**4.1 Logic State**—Positive True Logic will be used when referring to the states of transmitted inputs and received outputs. Referring to Appendix A, the input of the transmitter (marked as point Tx) and the output of the receiver (marked as Rx) will be in logic 1 state when driven or passively pulled to +V, and will be at a logic 0 state when driven to ground.

**4.2 Bus State**—The bus is in a logic 1 (high) state whenever Point A is at least 0.2 V more positive than Point B. The bus is in a logic 0 (low) state whenever Point A is at least 0.2 V more negative than Point B (Points A & B refer to Appendix A). The bus state is indeterminate when the differential voltage is less than 0.2 V.

4.2.1 LOGIC HIGH STATE—The bus will be in a logic 1 (high) state when all connected transmitters are idle or sending logic one. An Idle State is produced when all transmitters on the network are turned off. All nodes shall include means to pull the bus to a logic 1 (high) when all transmitters are off. (See Appendix A.)

4.2.2 LOGIC LOW STATE—The bus will be in a logic 0 (low) state when one or more transmitters are sending logic 0, which guarantees that logic 0 (low) dominates when the bus is in contention.

**4.3 Network Capacity**—The bus will support a minimum of 20 standard nodes where each node is comprised of the circuit defined in Appendix A. Deviations from this circuit must be carefully analyzed to determine impact on bus loading and noise margins over the common-mode range.

**4.4 Bus Termination**—Bus termination resistors as referenced in RS-485 are not required and shall not be used.

**4.5 Ground**—All assemblies using the link must have common ground reference.

**4.6 Wire**—A minimum of 18 gauge twisted pair wire, with a minimum of one twist per inch (2.54 cm) is required.

**4.7 Length**—This recommended practice is intended for but not limited to applications with a maximum length of 130 ft (40 m).

*5. Network Parameters*

**5.1 Network Topology**—The network interconnect shall use a common, or global bus.

**5.2 Network Access**—The method of access to the network is random.

5.2.1 BUS ACCESS—A transmitter shall begin transmitting a message only after an Idle State has continuously existed on the bus for at least a Bus Access Time. The transmitter must verify that the Idle State continues to exist immediately prior to initiating a transmission (that is, within one-half bit time).

5.2.1.1 *Bus Access Time*—Bus Access Time is a time duration equal to the minimum time of an Idle Line plus the product of two Bit Times and the Message Priority. This relationship can be expressed as:

$$T_a = T_i + [2 * T_b] * P$$

where: $T_a$ = Bus Access Time
$T_b$ = Bit Time, or period of one unit of information
P = Message priority
$T_i$ = Minimum time duration of an Idle Line

Note: The minimum time duration of an Idle Line is defined in paragraph 3.2.9. However, a transmitter which cannot distinguish between a Stop Bit and any other high logic state may not assume that $T_i$ has elapsed until it has received 19 consecutive high logic bits.

5.2.1.2 *Message Priority Assignment*—All messages will be assigned a priority from 1–8 as follows:

| Priority | Message Assignment |
|---|---|
| 1 and 2 | Reserved for messages that require immediate access to the bus |
| 3 and 4 | Reserved for messages that require prompt access to the bus in order to prevent severe mechanical damage |
| 5 and 6 | Reserved for messages that directly affect the economical or efficient operation of the vehicle |
| 7 and 8 | All other messages not fitting into the previous priority categories should be assigned a priority 7 or 8 |

The applications document shall define the priority associated with each message. In the event that more than one priority could be assigned to a particular message, the application document shall define each priority and the circumstances in which the priority is assigned.

5.2.2 BUS CONTENTION—All transmitters shall monitor the message identification portion of their message to determine if another transmitter has attempted to gain access to the bus at the same time. If a transmitter detects a collision, the transmitter shall relinquish control of the bus after completing the transmission of the current character or sooner if possible. After relinquishing control, the transmitter may attempt to regain access to the bus after a Bus Access Time has elapsed. An example bus reaccess procedure is shown in Appendix B.

*6. Protocol*

**6.1 Bit Time**—A Bit Time shall be 104.17 μs ± 0.5% (±500 ns). This is equivalent to a baud rate of 9600 bits per second.

**6.2 Character Format**—A character shall consist of 10 Bit Times. The first bit shall always be a low logic level and is called the Start Bit. The last (tenth) bit shall always be a high logic level and is called the Stop Bit.

This convention is consistent with standard UART operation. The remaining eight center bits are Data Bits that are transmitted Least Significant Bit (LSB) first.

### 6.3 Message Format

6.3.1 Message Content—A message appearing on the communication bus shall consist of the following:

Message Identification Character
Data Characters
Checksum

As indicated in paragraph 5.2.1, a message shall always be preceeded by an Idle State of duration equal to or greater than the appropriate Bus Access Time. The length of time between characters within a message shall not exceed 2 bit times.

6.3.2 Message Identification Character—The first character of every message shall be a Message Identification Character (MID). The permitted range of MIDs shall include the numbers 0–255. The MIDs 0–68 shall be assigned to transmitter categories as identified in Table 1. These assignments have been made to accommodate existing systems, or systems that may presently be under development, and to avoid conflicts which otherwise might arise if indiscriminate use of MIDs were permitted.

Message IDs 69–111 shall be allocated as reserved MIDs for transmitter categories beyond those which are identified in Table 1. These MIDs shall be individually assigned by the SAE Truck and Bus Electrical Committee, Electronics Interface Subcommittee upon petition by a manufacturer at the time a new transmitter category is identified, or when additional MIDs are required within a previously identified category. The content and format of the messages using the above assigned MIDs (0–111) is the responsibility of the transmitter. Content of format of the data within these messages is not defined in this recommended practice but should be identified in an appropriate applications document as described in paragraph 3.1.3.

Message IDs 112–127 are not assigned to any category and are not reserved for future assignment. These MIDs are available to any manufacturer or user for any message identification purpose outside the scope of this document.

Message IDs in the 0–127 range shall be defined in the manufacturer's applications document. It shall be the responsibility of the systems integrator or user to ensure that a particular MID is not used by more than one device on the same vehicle.

Message IDs in the range 128–255 shall be reserved for applications using formatted data as set forth in a recommended practice to be issued by the SAE Truck and Bus Electrical Committee Data Format Subcommittee. These MIDs shall only be used when the data format set forth within that recommended practice is strictly followed.

6.3.3 Data Characters—Data Characters shall be characters that convey the intelligence of the message and shall conform to the Character Format as defined in paragraph 6.2 of this document. The eight bit Data Character may be given any value from 0–255. The Data Characters shall be defined in an appropriate applications document at the option of the supplier. The application document shall define parameters, parameter order, scaling and error detection/correction coding if applicable.

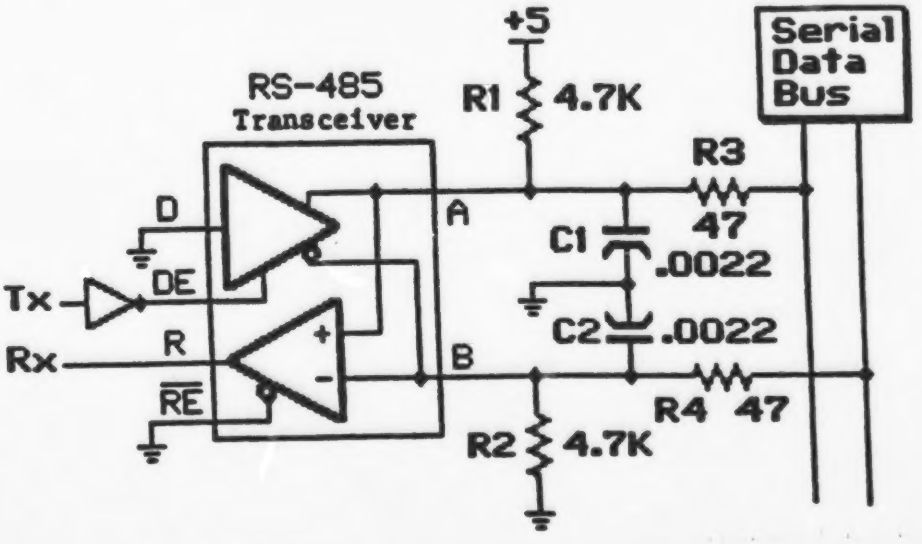
TABLE 1—MESSAGE IDENTIFICATION CHARACTER ALLOCATION

| Mid Range | Transmitter Category |
|---|---|
| 00–07 | Engine |
| 08–09 | Brakes, tractor |
| 10–11 | Brakes, trailer |
| 12–13 | Tires, tractor |
| 14–15 | Tires, trailer |
| 16–17 | Suspension, tractor |
| 18–19 | Suspension, trailer |
| 20–27 | Transmission |
| 28–29 | Electrical charging system |
| 30–32 | Electrical |
| 33–35 | Cargo refrigeration/heating |
| 36–40 | Instrument cluster |
| 41–45 | Driver information center |
| 46–47 | Cab climate control |
| 48–55 | Diagnostic systems |
| 56–61 | Trip recorder |
| 62–63 | Turbo-charger |
| 64–68 | Off-board diagnostics |
| 69–111 | Reserved—to be assigned by electronic interface subcommittee (see paragraph 6.3.2, paragraph 2). |
| 112–127 | Unassigned—available for use |
| 128–255 | To be assigned by data format subcommittee (see paragraph 6.3.2, paragraph 5). |

6.3.4 Checksum—The last character of each message shall be the two's complement of the sum of the MID and the Data Characters. Simple message error detection may be implemented by adding the Checksum to the sum of all previous message characters (including the MID). The eight bit sum will be zero, neglecting the CARRY, for a correctly received message.

6.3.5 Message Length—Total message length, including MID and Checksum, shall not exceed 21 characters. Exceptions may be made when the engine/vehicle is not running.

## APPENDIX A
## SERIAL DATA BUS STANDARD NODE
## (UNI-POLAR DRIVE WITH PASSIVE TERMINATION IN EACH MODULE)



1. This circuit utilizes standard RS-485 transceivers (less than or equal to one RS-485 unit load) connected to drive the differential data bus to the logic zero state only (uni-polar drive). In the above circuit, a standard RS-485 receiver may be used in place of a transceiver in applications where data need not be placed on the bus (that is, receive only).

2. The logic one state (also idle state) is controlled by pullup resistor R1 and pulldown resistor R2.

3. The transceiver output impedance, C1 and C2, form the transmit filter for transient and EMI suppression (approximately 6 MHz low pass).

4. R3, C1, R4, and C2 form the receive filter for EMI suppression (approximately 1.6 MHz low pass). These parts also form a pseudo line termination at high frequencies.

5. The active (high-to-low) transition delay is approximately 0.6 μs at the receiver with 2 nodes on the bus and 2.3 μs with 20 nodes on the bus.

6. The passive (low-to-high) transition delay at the receiver remains at 10 μs with any number of loads on the bus (up to 20).

7. The values shown were chosen for use with commercially available RS-485 drivers to provide maximum fan-out, EMI suppression and bus termination. Remaining nodes may be in either the powered or unpowered state.

8. This method of uni-polar drive prevents unresolved contention (logic zero always wins).

9. The resistors shown should be 5% parts to assure sufficient noise margin under worst case conditions. R3, R4, C1, and C2 should be balanced within 10% on each side of the data bus to minimize common mode electromagnetic radiation.

## APPENDIX B
## EXAMPLE BUS REACCESS PROCEDURE

A method for reaccessing the bus can be described by the following example:

Sequence of Events:

1. First crash occurs for the current attempt to access the bus.

2. Each device wishing to access the bus then waits their predefined Bus Access time (as described in paragraph 5.2.2).

3. Second crash occurs for the same attempt to access the bus.

4. Any device that has experienced two consecutive crashes in its attempt to transmit the same message shall follow the bus access procedure defined in paragraph 5.2.1 but with the Bus Access Time calculated as follows:

$$T_a = T_i + 2 + P_r \times T_b$$

$T_i$ and $T_b$ are defined as in paragraph 5.2.1.1.

$P_r$ = A 3 bit psuedo random number such as the 3 least significant bits of the stack pointer.

For example, if 18 is the location of Stack Pointer Register, the contents of this register is the stack pointer. This value will be ANDED with 0007 which results in a number from 0–7. $P_r$ would therefore be a value from 0–7.

5. If any more consecutive crashes occur, the procedure described in No. 4 is repeated.

This example addresses the recognized possibility that two or more devices could continue to crash if their priorities were the same. The above method would greatly reduce the possibility of a third crash with the same device or devices.